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Xella – Interior insulation – Final report, stage 1

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Content

Dansk resumé

Formålet med projektet er, at teste Ytong Multipor produktet til indvendig efterisolering, således at det kan udbredes på markedet. Da der opleves en indgroet skepsis mod indvendig isolering, som er svær at overkomme uden en lang række test, dokumentation og gode eksempler.

Ytong Multipor er et markedsintroduceret mineralsk og miljøvenligt materiale til indvendig isolering, der kan realisere det uforløste potentiale for energireduktion i bygninger med bevaringsværdige facader. Det bliver muligt, at isolere bygninger indvendigt samtidig med, at det gode indeklima bevares og risikoen for fugtproblematikker minimeres. Ytong Mulitipor imødekommer fugtproblematikken med et diffusionsåbent, kapillaraktivt, mineralsk og dampspærrefrit system og med en høj isoleringsevne, skaber produktet mulighed for at opnå en reduktion i energiudslippet i de bygninger, der oprindeligt ikke vil blive efterisoleret. Yderligere undersøges om en stribe Ytong Plade med en lavere isolerigsevne foran træelementer i muren kan bruges som supplement i særlig krævende situationer, som f.eks. murværk med indlejrede træelementer.

Den nærværende delrapport præsenterer resultaterne fra en række projekter med fokus på indvendig isolering af massivt murværk med Ytong Multipor, hvor der tages stilling til følgende problemstillinger: skimmelvækst og andre fugtrelaterede problemer, systemets robusthed i forhold til ophæng af elementer og dets slagfasthed, samt undersøgelse af forskellige overfladebehandlinger (diffusions-åben og diffusions-tæt maling) på de indvendige overflader og dets påvirkningen på murværkets fugt balance ved brug af Multipor systemet.

Projekt resultaterne indikerer i forhold til skimmelvækst og andre fugtrelaterede problemer, at hydrofobering af de udvendige overflader har både en positiv og en negativ effekt på fugt balancen i murværket, at den tilsigtede kuldebro foran den indlejrede træ rem reducerer fugt indholdet, samt at en kombination af udvendig hydrofobering af murværket og et sænket indendørs fugtindhold (f.eks. til en indeklima klasse 2, ved brug af mekanisk ventilation) kunne nedbringe den relative fugtighed til et acceptabelt niveau med lav risiko for skimmel og råd problem. Robustheds undersøgelserne indikerer acceptable resultater for slagfasthed og forskydning, hvorimod der konstateres en under middel udtræksstyrke. Undersøgelser omkring overfladebehandlinger indikerer at den diffusionstætte maling havde en effekt på væggens dampgennemtrængelighed, men at denne effekt var meget lille for det enkelte lag og at der derfor skulle påføres et betydeligt antal lag før det ville føre til fugt relaterede problemer.

Den nærværende delrapport er grundet udenlandske partnere skrevet på engelsk.

1. Introduction

1.1 Background

The purpose of the project is to test the Ytong Multipor product for interior post-insulation, in order for the product to expand on the market. There is a deep scepticism about the use of interior insulation, which is difficult to overcome without test results, documentation and good examples.

Ytong Multipor is a market-launched mineral and environmentally friendly material for interior insulation that can realize the unresolved potential for energy reduction in buildings with worth preserving facades. It will be possible to insulate buildings inside while maintaining the good indoor climate and minimizing the risk of moisture problems. Ytong Mulitipor responds to the moisture problem with a diffusion-open, (low) capillary active, mineral and vapour barrier free system, and with high insulating properties, allows the product to achieve a reduction in energy emissions in the buildings that will initially not be post-insulated. In addition, it is investigated if the Ytong Plate with a lower insulation capability can be used as a supplement in particularly demanding situations, such as masonry assemblies with embedded wooden elements.

1.2 Project organization

Xella Danmark had the role of project manager and applicant.

From Xella Denmark, the following people participated:

- Frederik Johnsson (CEO Xella Skandinavia)
- Niels-Jørgen Pallesen (Former CEO Xella Skandinavia)
- Johan Vestergaard (Xella Danmark)
- Jens Lauridsen (Former head of technical department Xella Danmark)
- Xella T&F – technicians from Xella Germany and Xella Denmark.

DTU BYG played a central role in the project, and the following people participated:

- Lektor Søren Peter Bjarløv (Project manager)
- Ph.d. student Tommy Riviere Odgaard
- Ph.d. student Nickolaj Feldt Jensen

1.3 The experimental set-up

The original idea for the experimental set-up, presented in the application for the project, was to construct a test building with the interior measurements 3x3 m, with a room height of 2.6 m. The test room would have a heated story below, and a cold attic space above, with an insulated attic floor. The walls would be constructed as solid single layer masonry walls, two walls would be fitted with 2 “dannebrog” windows. In addition to the test building, the Ytong Multipor system would be installed in test rooms in one or more apartments in a multi-storey building. The chosen multi-storey building should have a floor structure consisting of wooden beams, resembling buildings from the target group. However, the experimental set-up was re-designed, around the use of a 40 feet insulated reefer containers, into which 8 different masonry assemblies were constructed. The masonry assemblies were constructed as a 3-dimensional set-up including a wooden floor structure and a ½-stone adjacent internal masonry wall. Between the masonry assemblies, adiabatic conditions were established, in order to create 1-dimensional heat and moisture transport through the assemblies.

In addition to the re-design of the experimental set-up, the fond, Realdania, decided that the original project should be split into two separate project stages. Stage 1 would focus on the experimental set-up at DTU, hereunder the investigation of the Ytong Multipor system with respect to mould and other moisture related issues, robustness of the system, as well as the influence of interior surface treatments. While stage 2 would focus on the installation of the Ytong Multipor system in test apartments.

1.4 Project progress

The project progress is presented below in Table 1, which includes activities, sub-activities, the original deadlines as well as time extensions for the individual activities.

Table 1: Project progress

Original activity	Sub-activity	Original month	1. extension month	2. extension month
Project granted by RealDania		-	2014: June	2014: June
Test 1 – Mock up		2013: November to 2014: January	2014: August to 2015: May	2014: August to 2015: May
	Build base walls		2014: September to 2014: October	2014: September to 2014: October

	Dry out		2014: October to 2015: April	2014: October to 2015: April
	Apply insulation/start up experiment		2015: April to 2015: May	2015: April to 2015: May
Test 2 – Apartment		2013: December to 2014: January	→ Phase 2	→ Phase 2
Activity 3 – Monitoring and data processing		2014: February to 2015: February	2015: May to 2016: May	2015: May to 2017: May
Activity 4 – Documentation and dissemination		2015: February to 2016: January	2016: May to 2016: November	2017: May to 2017: December

1.5 Report structure

The present report is divided into three chapters: Chapter 2) Mould growth and other moisture related issues, presents the experimental- and simulation results for the hygrothermal conditions in the wall constructions, and the potential risk for mould growth, wood decay and frost damage. Chapter 3) Robustness and surface treatments, presents the experimental robustness results carried out for the Multipor insulation system, as well as the experimental- and simulation results regarding the use of diffusion-open and diffusion-closed interior surface treatments. Chapter 4) Results, summarises and wraps-up the intermediate results from the previous chapters.

2. Mould growth and other moisture related issues

2.1 Experimental and theoretical investigation of Interior insulation of solid brick walls with foam concrete and another silicate based material

2.1.1 Project description

Results and figures presented below are from the master's thesis by former MSc. students at DTU, Daniel Dysted and Hasse Sandholdt (Dysted & Sandholdt, 2015). Their project addressed the use of internal insulation systems without the use of a vapour barrier, and consisted of three parts:

- Full scale experiment: 1-dimensional steady state measurements of three 1.5 stone solid masonry walls (348mm) with 12 mm interior lime mortar render, with the exterior surface placed within specially designed cooling chambers, maintaining a relative humidity range of 80-90% and a temperature range of 2.8-3.8°C (corresponding to the average Danish winter temperature). The indoor climate was set to 60% and 20°C respectively. The effect of wind and rain was not considered within this project. 1-dimensional conditions were obtained by sealing the wall samples with a vapour retarder, and insulate the sides. The Multipor interior insulation system (100 mm) was assessed, with regular diffusion-tight paint and diffusion-open paint treatment on the interior surface. To determine whether these would influence the moisture content in the wall. Temperature and relative humidity were logged every minute through the use of three digital HYT 221 sensors (by Innovative Sensor Technology IST AG) within each wall sample, as well as sensors installed within the cooling chambers and in the indoor environment. The experiment was carried out over a period of two months (1600 hours). The accuracy of the digital HYT221 sensors is for relative humidity measurements ±1.8% at 23°C, between 0% to 90% relative humidity, while for temperature measurements ±0.2K between 0°C to 60°C. The sensors have a measurement range of 0% to 100% relative humidity, and temperatures from -40°C to 125°C (IST, 2014).

- Material properties: Within this project the following material properties were determined for the Multipor insulation (method mentioned by name in the brackets, no description will be provided in this report):

    - Water vapour diffusiveness parameters (cup experiment).
      The cup experiment was also carried out for the testing of Flügger Flutex 5 diffusion-tight paint, a commonly used interior wall paint in Denmark, KEIM Ecosil-ME silica based diffusion-open paint (S_d > 0.01m), and the primer KEIM Special fixativ. The paint layers were tested from raw gypsum board, then with primer, and then up to a total of four paint layers.
    - Thermal conductivity (guarded hot plate experiment, according to EN 12664, 2001)
    - Capillary suction tests (Laboratory of Building Materials (LBM) experiment number 1)
    - Density and porosity (Laboratory of Building Materials (LBM) experiment number 2)

- Theoretical investigation in Delphin: Two 1-dimensional wall assemblies were modelled in Delphin corresponding the 1.5 stone solid masonry walls from the experimental set-up with interior rendering and insulation system. One model using Flügger Flutex 5 paint, and one using the diffusion open KEIM paint system (primer and paint). The assessment of the two wall models were carried out under both transient and steady state conditions. The transient models were carried out 3-year simulations, with 1-year outdoor climate conditions cycled (DRY weather data), while the indoor conditions were set to a temperature of 20°C and a Relative Humidity of 60%. The steady state models were carried out using indoor conditions set to 20°C and 60% respectively, while the outdoor conditions were set to 3.3°C and 85% respectively. Material properties (water vapour diffusiveness parameters, capillary suction, density, porosity and moisture diffusivity) obtained from the material experiments were used within the Delphin simulations for accurate simulation results. For untested materials/material properties, suitable material models were selected from the Delphin database. Furthermore, for better comparison between the Delphin models and the experimental set-up, rain models were neglected for the Delphin simulations.

2.1.2 Intermediate results

The results for each for the three parts are presented below.

- Full scale experiment:

  For the experimental set-up, the reference wall showed high relative humidity near the interior surface (sensor locations b and c) already before the interior insulation (picture 1 of Fig. 1), around 92-96%. After the application of the insulation, then relative humidity near the interface (sensor locations b and c) increased to 100% (picture 2 of Fig. 1).

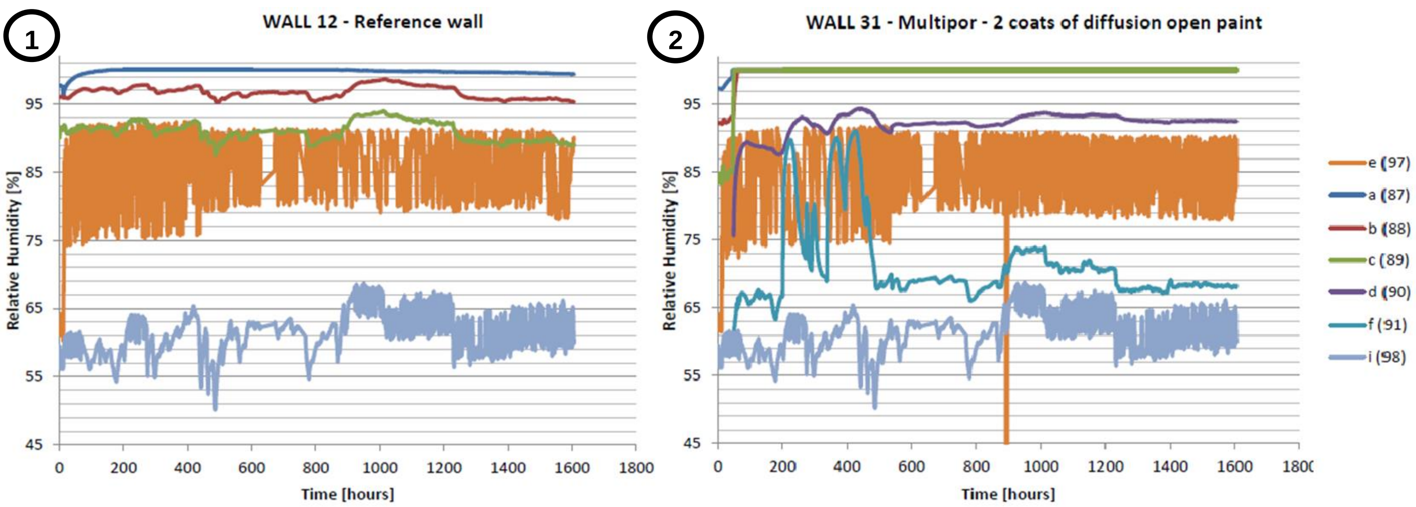


Fig. 1.: Experimental result. 1) Reference wall. 2) 2 layers of diffusion-open paint.

The third sensor, d, near the interface showed a slightly lower relative humidity around 93-95%. After a sharp increase around the 200th to 500th hour of the experiment, the relative humidity at the interior surface, f, was relatively steady around 66-72%. Lastly, a comparison between the use of 2 layers of diffusion-open and diffusion-tight paint on the interior surface (not shown in this report). Indicated almost no change for the relative humidity at the interface sensors b and c, while a 2-3% decrease in the relative humidity was seen for the interface sensor d, using 2 layers of the regular diffusion-tight paint. Dysted and Sandholdt concluded on this part that although the experimental results showed high relative humidity at the interface, as the measurements showed a slight decline over the course of the experiment, this could indicate that the wall assemblies are still not in moisture equilibrium. Thus, making it difficult accurately compare the different variations. However, for the experimental period in question, the moisture conditions indicate a risk of mould growth near the interface after application of the interior insulation, while very little risk is seen for the interior surface.

- Material properties:

  Dysted and Sandholdt determined through various tests several material properties of the Ytong Multipor as well as the other materials used in the experimental set-up, the test results are presented in Table 2 below. Regarding the properties of the Multipor, the following material properties were specified in the technical datasheet (dated June 2012): λ = 0.042 W/mK, ρ = 115 kg/m^3, μ = 5 [-]. A comparison with the test results showed a thermal conductivity 0.046±0.002 W/m·K, corresponding to a difference of 5-14%, while a 17% difference was determined for the density, and 38% difference for the vapour resistance factor. Dysted and Sandholdt stated that the differences between test results and the Multipor product specifications could be related to differences in the measurement techniques. Based on the moisture transport properties determined by the material tests, it was concluded by Dysted and Sandholdt that the Multipor insulation has low capillary suction, thus liquid moisture transport will occur slowly through the material. This correlate with the experimental results obtained by (Vereecken & Roels, 2014), that the Multipor insulation do show capillary transport properties.

- Theoretical investigation in Delphin:

  The steady-state simulations showed quite high relative humidity at the interface, in the range of 94-97%, while only around 70% at the interior surface, as shown in Table 3. However, it should be noted that these simulations were carried out using an indoor relative humidity of 60%. The simulation results showed no difference between two and four layers of regular, diffusion-tight paint. No simulations were carried out using diffusion-open paint, a comparison between the diffusion-open and diffusion-tight paints is therefore not possible.

Table 2: Test results for the material properties

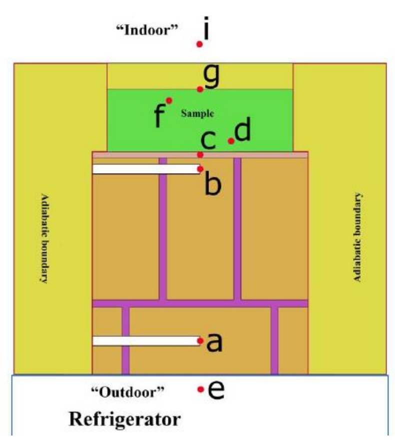
MATERIALS	*LBM 1*	*LBM 2*		*Guarded hot plate*	*Isometer*	*Cup method*	
	Water up-take coefficient	*Density*	*Open porosity*	*Thermal Conductivity*		*Vapour resistance factor*	*Water vapour permeability*
	Aw $[kg/m^2s^{0.5}]$	ρ $[kg/m^3]$	*p0* [-]	λ [W/mK]		μ [-]	δ $[kg/(m \cdot s \cdot pa)]$
Brick	0.313	1713	0.376		0.518	11.56	$17.1 \cdot 10^{-12}$
Lime mortar (carbonated)	0.463	1732	0.326		0.389	7.54	$26.2 \cdot 10^{-12}$
Lime mortar (NON-carbonated)	0.616	1738	0.339		0.370	7.2	$28.2 \cdot 10^{-12}$
Multipor	0.002	95	0.961	0.046	0.049	3.11	$63.2 \cdot 10^{-12}$
COATS OF PAINT						*Vapour diffusion resistance* Z $[(m^2 \cdot s \cdot Gpa)/kg]$	
Raw Gypsum board (13 mm)						0.32	
Paint (primer only)						0.1	
Paint (1 coat of paint + primer)						1.13	
Paint (2 coats of paint +primer)						1.73	
Paint (3 coats of paint + primer)						2.31	
Paint (4 coats of paint +primer)						2.9	

Describing equation of vapour diffusion resistance (Z-value) based on number of layers of ordinary Flutex 5 paint:

$$Z = 0.59n + 0.55$$

Table 3: Results from the Delphin steady state simulations

	Temperature [°C]		Relative humidity [%]	
No. of paint layers (diffusion-tight)	2	4	2	4
Sensor point a	3.8	3.8	84	84
Sensor point b	7.5	7.5	97	97
Sensor point c	7.7	7.7	97	97
Sensor point d	9.7	9.7	94	94
Sensor point f	16.9	16.9	71	71



The transient simulations showed similar to the steady state simulations high relative humidity at the interface sensors (b, d, d) during the entire heating season, up to 94-97%, while the late summer / start autumn showed a low peak of 65-70% relative humidity. As it was the case for the steady state simulations, no difference was seen for the temperature or relative humidity at any of the sensor locations between 2 and 4 layers of diffusion-tight paint on the interior surface, as shown in Fig. 2. Additionally, as it was the case for the steady state simulations, no simulations were carried out using diffusion-open paint, a comparison between the diffusion-open and diffusion-tight paints is therefore not possible. For the interior surface temperature, the transient simulations showed 16-20°C. Thus indicating that there should be no risk of condensation on the interior surfaces.

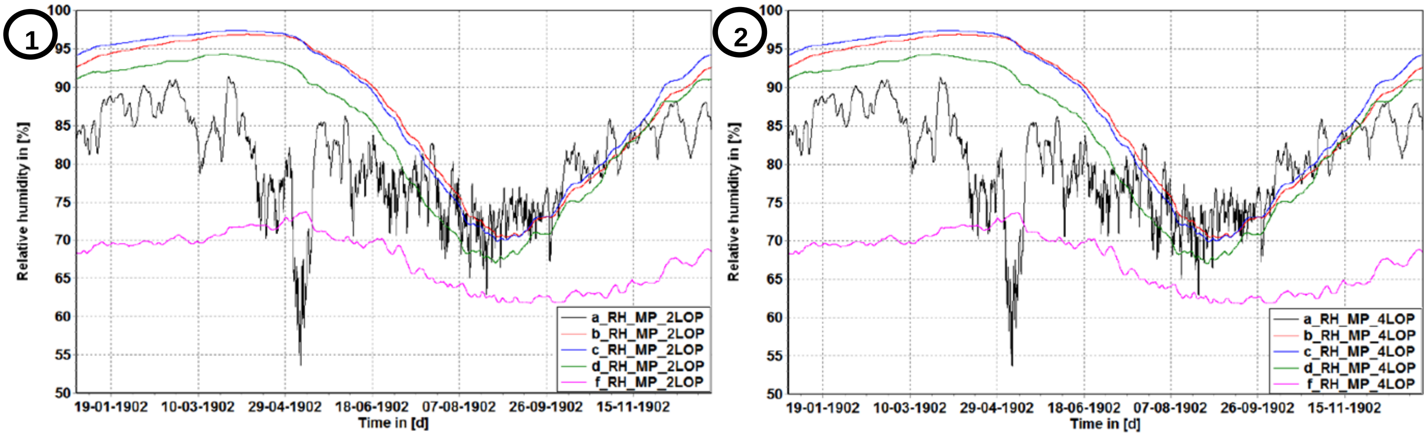


Fig. 2.: Transient Delphin simulation results. 1) 2 layers of diffusion-tight paint. 2) 4 layers of diffusion-tight paint.

2.2 Hygrothermal modelling of internal insulation to solid masonry walls

2.2.1 Project description

Results and figures presented below are from the master's thesis by former MSc. student at DTU, Peter Otiv (Otiv, 2016). In his thesis, Otiv carried out 1-D hygrothermal simulations in the software Delphin for two interior insulated masonry assemblies. The masonry assemblies consisted of 348mm yellow softmolded historical brick, 10mm historical lime plaster, 8mm glue mortar, 100 mm lightweight mineral insulation, and 8mm glue mortar. One of the masonry assemblies had a bare exterior surface, while the other one had a hydrophobized exterior surface. The hydrophobization was carried out by reducing the water uptake coefficient, A_w, of the outermost 10mm of the historical brick by a factor of 1000. Note that the materials used for the Delphin simulation were obtained from the Delphin material database, with exception of the yellow softmolded historical brick. The material properties for the historical brick were obtained from a previous study carried out by DTU (Dysted & Sandholdt, 2015). Both masonry assemblies were simulated with a cardinal direction towards southwest with a compass angle of 225°.

Initially, the Delphin models were validated using measured data, including measured data from sensor location one to four within the two masonry assemblies, as well as for the interior and exterior climates. The model validation by Otiv will not be presented in this report, for more information the reader is refered to (Otiv, 2016). After the model validation, the exterior climate was changed to those of Copenhagen, Esbjerg and Aalborg, in order to investigate how the interior insulated masonry assemblies would perform under different typical Danish climate conditions. For the comparison between the three locations, Design Reference Year (DRY) climate data from the Danish Meteorological Institute was used. Note that the DRY data sets did not include rain data. Rain data for Kgs. Lyngby was therefore used for all three locations. Otiv mentions that this may overestimate the influence of the rain at the other locations, as Kgs. Lyngby generally receives more precipitation in comparison to the other locations. Regarding the initial conditions of the masonry assemblies, the default settings of 80% relative humidity and 20°C were used. However, note that a two-year initial simulation period using cyclic DRY climate data for Copenhagen was used in order to allow the materials to reach a quasi-steady state before introducing the measured data recorded at the experimental set-up at DTU, Kgs. Lyngby, as recommended in the SUSREF guidelines (Peuhkuri, et al., 2011). This process was however only used for the model validation. For the simulations using climate data from other geographical locations (Copenhagen, Esbjerg and Aalborg), the default settings were used and the DRY climate data was simulated for a period of three years. From the three simulated years using DRY data, the last year was taken further for assessment.

As for the boundary conditions, Otiv altered several coefficients under the boundary conditions during the validation process and the values used for the final wall models, for each of the altered coefficients are shown in Table 4. The remaining coefficients were left as default.

Table 4: Boundary conditions

Boundary condition	Coefficient	Position	Value
Rain	Rain exposure coefficient		0.6
Short wave solar radiation	Reflection coefficient of the surrounding ground (albedo)		0.2
Long wave solar radiation	Emission coefficient of the building surface		0.7
Heat conduction	Exchange coefficient for heat flow	External Internal	25 W/m^{2}K 4 W/m^{2}K
Vapour diffusion	Exchange coefficient for vapour diffusion	External Internal	2e-7 s/m 3e-8 s/m

Finally, the moisture conditions within the masonry assemblies under the different typical Danish climate conditions were assessed with respect to mould growth at sensor locations 3 and 4 using the VTT mould model (Ojanen, et al., 2011), wood decay using the VTT wood decay model (Viitanen, et al., 2010), and frost damages using Delphins built-in “Ice volume to pore volume ratio” model (Sontag & Nicolai, 2013). Note that for the evaluation using the damage models, a worst-case scenario was used, with a material sensitivity of sensitive and almost no decline. Note that assessment of the moisture conditions was only carried out for Copenhagen, Esbjerg and Aalborg, not for Kgs. Lyngby.

2.2.2 Intermediate results

The resulting relative humidity for the four sensor locations simulated in Delphin for the two validated masonry assemblies are shown in Fig. 3, it can be seen that the hydrophobization on the exterior surface had a positive effect on the two simulated masonry assemblies. As the relative humidity was greatly reduced at all four sensor locations. The simulation results do however indicate that although the hydrophobized wall maintains a low relative humidity level during the summer period, by limiting moisture from entering from the warm, moist exterior climate, it also indicates that the hydrophobization has a negative effect during the winter (picture 1-3 of Fig. 3). As the moisture inside the wall is limited from evaporating to the cold, dry exterior climate, thus resulting in the high relative humidity levels during the winter period. The hydrophobized surface generally indicated a positive effect for all three geographical location investigated in this study, as shown in Fig. 4, Fig. 5 and Fig. 6, and the indication regarding the hydrophobization treatment are also visible for the other locations. To avoid confusion, it should be noted when reading the following graphs for the other geographical locations, that the y-axis is different between the hydrophobized and the un-hydrophobized wall.

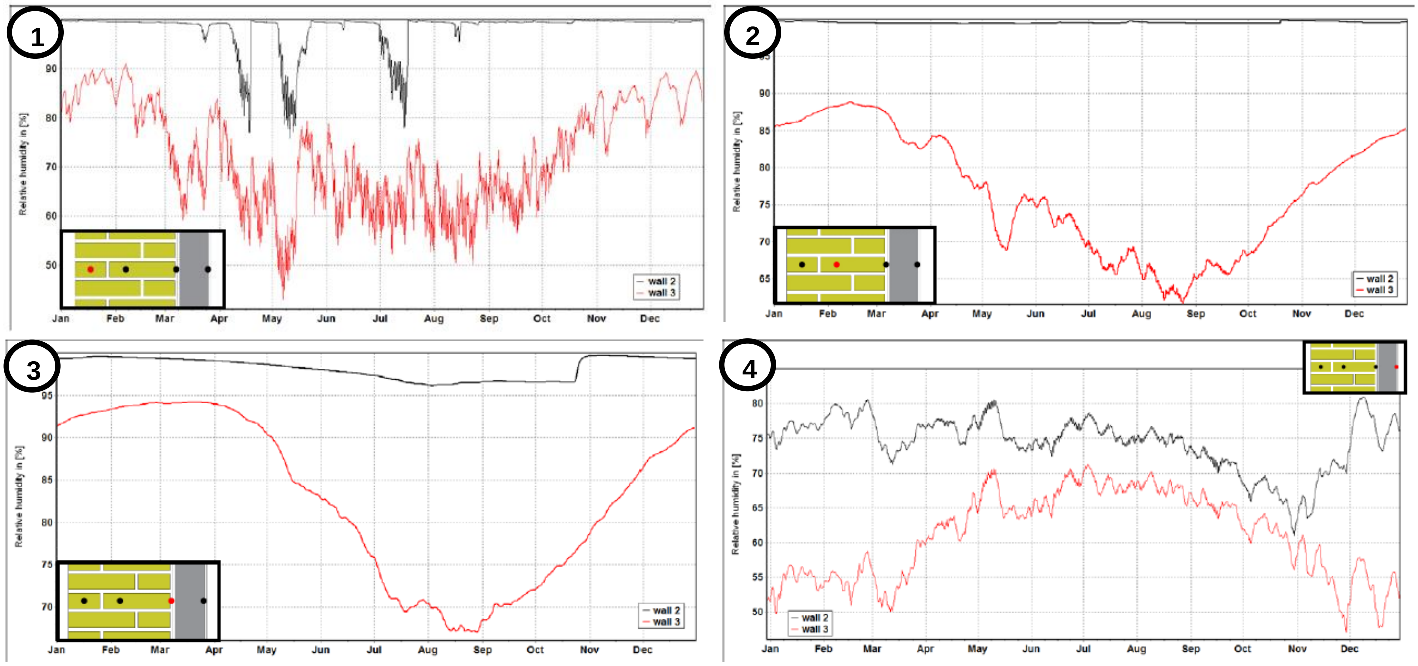


Fig. 3.: Simulation results for Kgs. Lyngby, relative humidity for the hydrophobized wall (Red) and the un-hydrophobized wall (Black). 1) Sensor location 1, near the exterior surface. 2) Sensor location 2, middle of the masonry wall. 3) Sensor location 3, at the interface between the masonry wall and the insulation board. 4) Sensor location 4, behind the interior surface material.

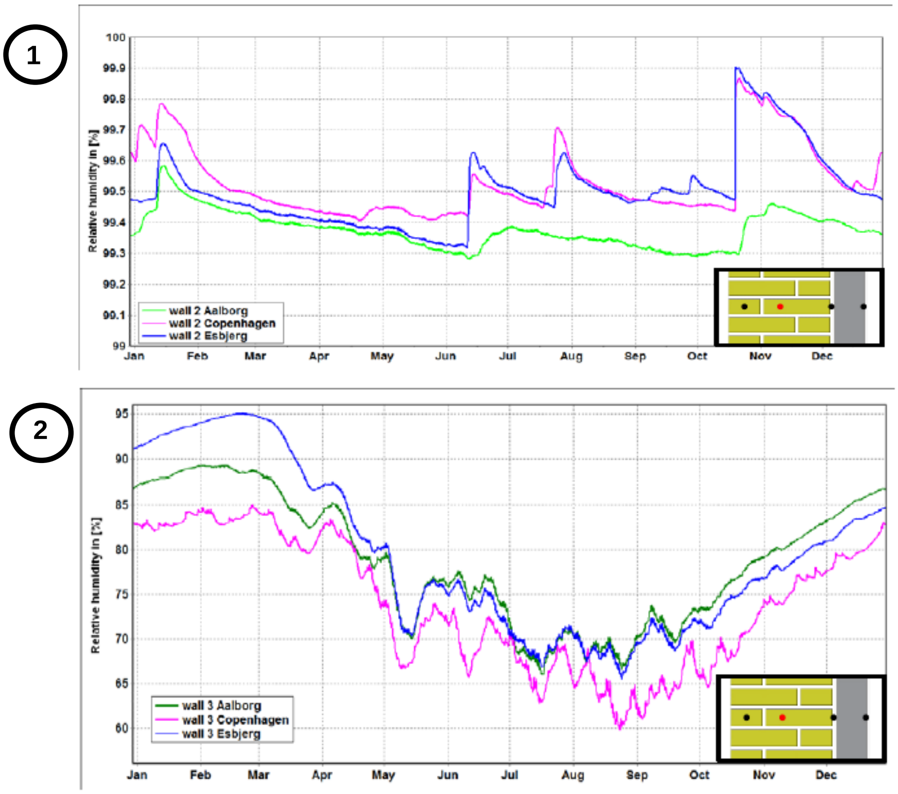


Fig. 4.: Comparison between simulation results for Copenhagen (Pink), Aalborg (Green) and Esbjerg (Blue), relative humidity at sensor location 2, in the middle of the masonry wall. 1) The un-hydrophobized wall. 2) The hydrophobized wall.

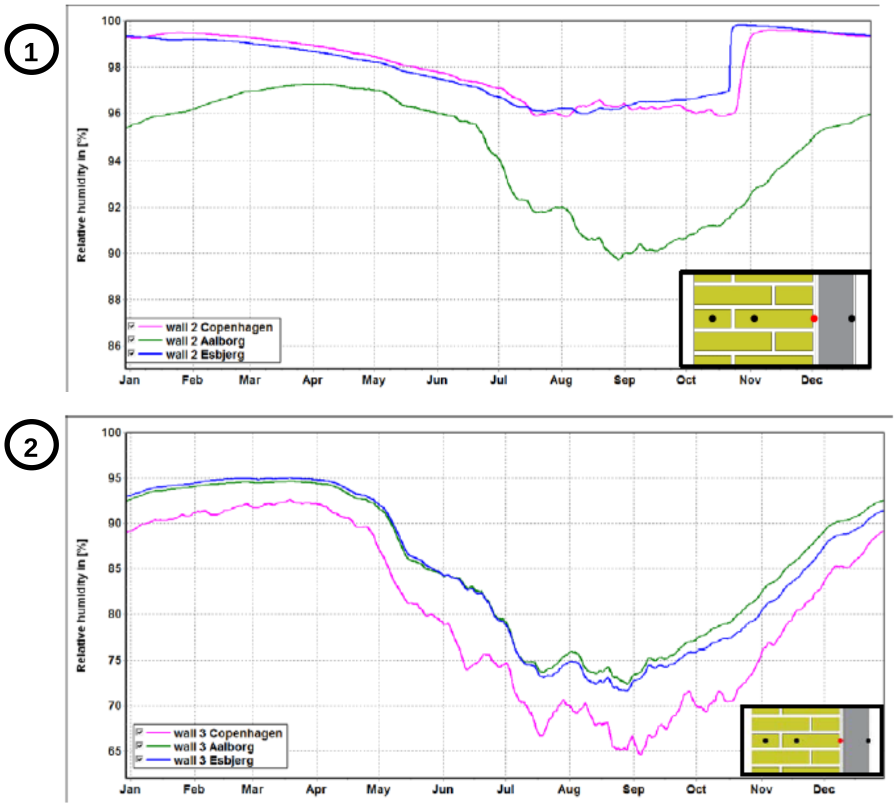


Fig. 5.: Comparison between simulation results for Copenhagen (Pink), Aalborg (Green) and Esbjerg (Blue), relative humidity at sensor location 3, in the middle of the masonry wall. 1) The un-hydrophobized wall. 2) The hydrophobized wall.

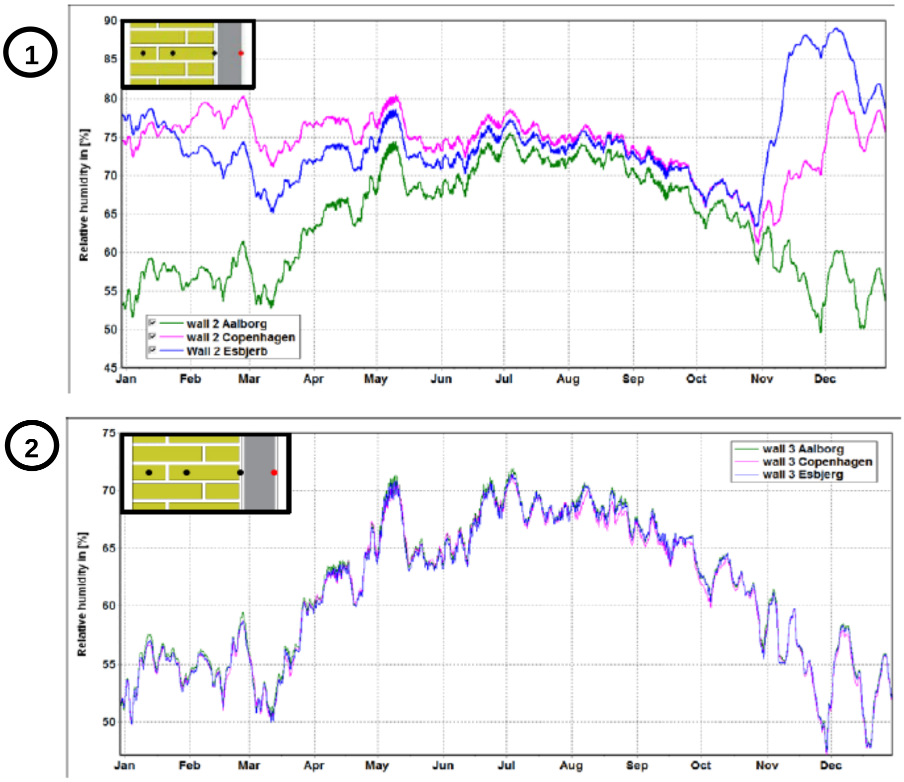


Fig. 6.: Comparison between simulation results for Copenhagen (Pink), Aalborg (Green) and Esbjerg (Blue), relative humidity at sensor location 4, in the middle of the masonry wall. 1) The un-hydrophobized wall. 2) The hydrophobized wall.

Regarding the evaluation using damage models, the ice volume to pore volume model predicted no risk of frost damages, as none of the two assemblies at any of the locations crossed the critical ice/pore volume ratio of 30%, set as critical limit (not shown figuratively in this report). For the wood decay model, Otiv's results indicated a large and steady mass loss at both the middle of the masonry wall (sensor 2) and at the interface (sensor 3) for the un-hydrophobized wall (picture 1, 3, and 5 of Fig. 7). After the hydrophobization of the exterior surface, the mass loss in the middle of the masonry wall (sensor 2) was predicted to be at 0% for both Copenhagen and Aalborg after three years, while at 0.5% for Esbjerg. At the interface (sensor 3), the mass loss was predicted to be reduced to around 2-4%, however, a 2-2.5% mass loss each year do seem to occur for all three locations (picture 2, 4, and 6 of Fig. 7). The mould model predicted no or acceptable levels of mould growth on the interior surface (sensor 4) for both the un-hydrophobized- and the hydrophobized walls. While at the interface (sensor 3), the un-hydrophobized wall reached mould index values between 3 and 3.5 after approximately 1-1½ year. Corresponding to mould growth beyond the microscopic level at the interface between the masonry wall and the insulation boards (picture 1-3 of Fig. 8Fig. 3.:). For the hydrophobized assembly the mould model predicted the peak mould index values between 2 and 2.25 for the three locations (picture 1-3 of Fig. 8).

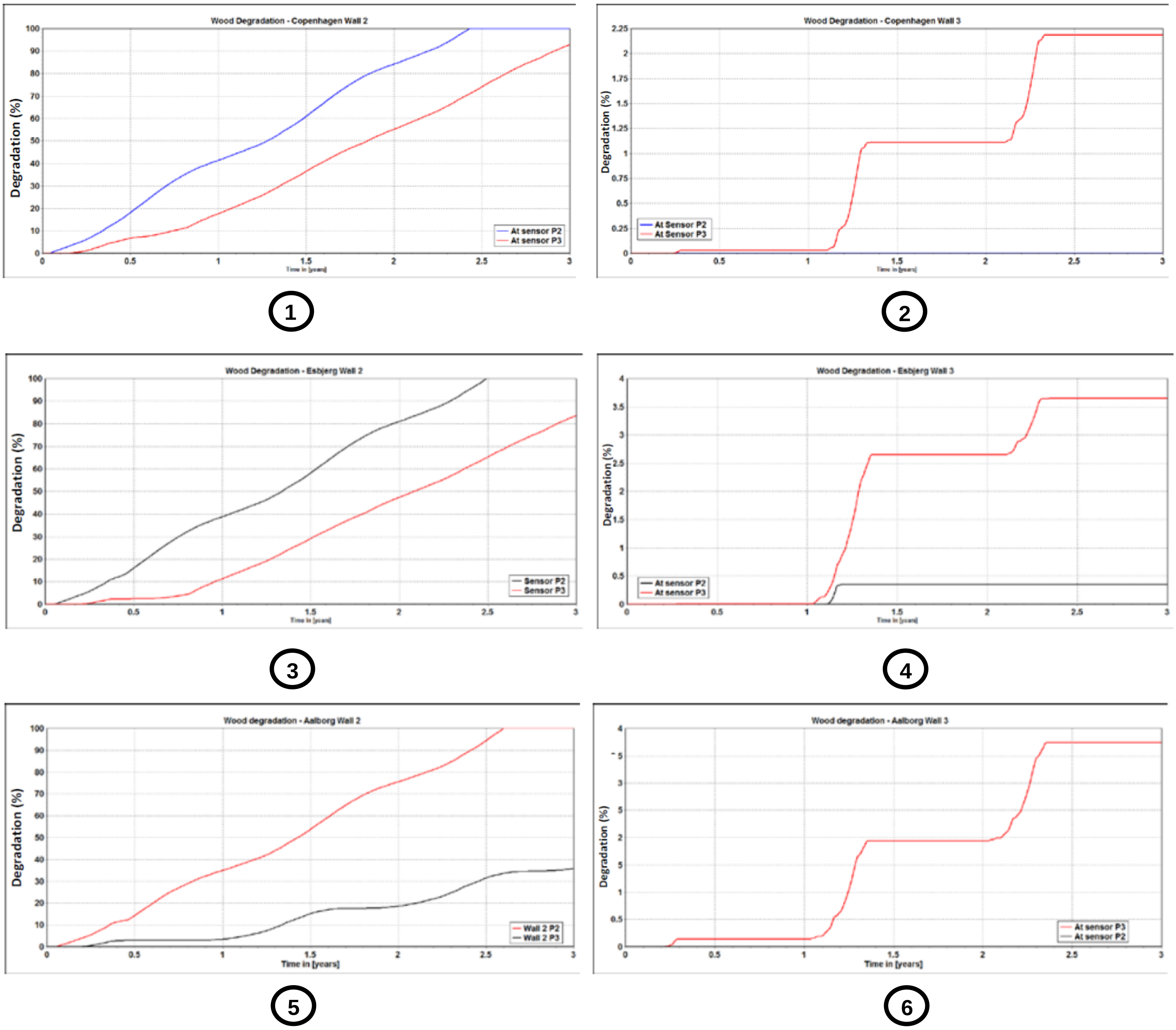


Fig. 7.: Simulated wood decay for Copenhagen for the un-hydrophobized wall (1) and the hydrophobized wall (2). Esbjerg for the un-hydrophobized wall (3) and the hydrophobized wall (4). Aalborg for the un-hydrophobized wall (5) and the hydrophobized wall (6). Sensor 2 in the middle of the wall (Copenhagen=blue, Esbjerg=black, Aalborg=Red) and sensor 3 at the interface (Copenhagen=red, Esbjerg=red, Aalborg=black).

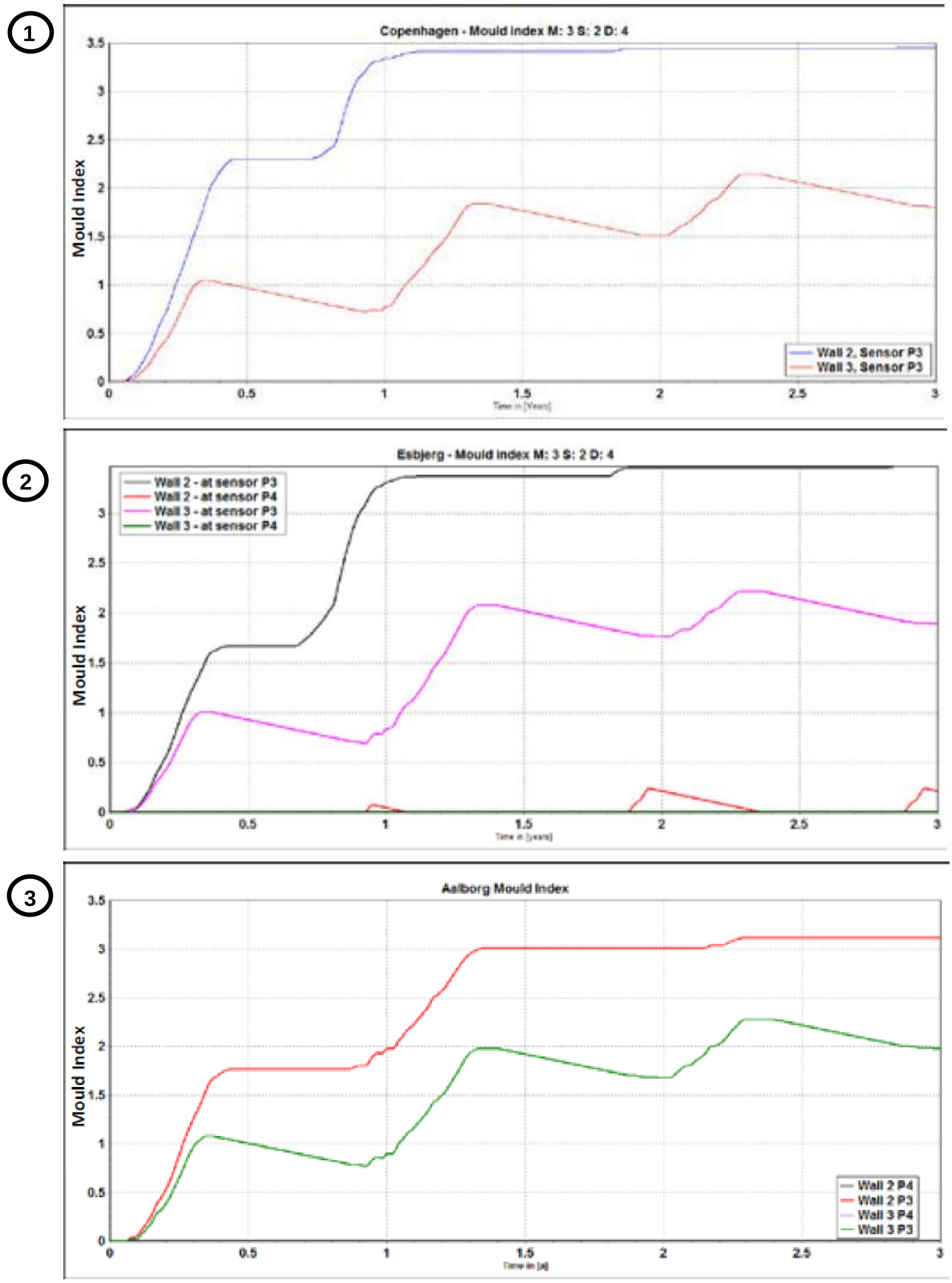


Fig. 8.: Simulated mould index for Copenhagen (hydrophobized=red and un-hydrophobized=blue), Esbjerg (hydrophobized sensor 3=pink, sensor 4=green, and un-hydrophobized sensor 3=grey and sensor 4=red), and Aalborg (hydrophobized sensor 3=light blue, sensor 4=green, and un-hydrophobized sensor 3=grey and sensor 4=red).

2.3 Influence of hydrophobization and deliberate thermal bridge on hygrothermal conditions of internally insulated historic solid masonry walls with built-in wood

2.3.1 Project description

Results and figures presented below are from the article by industrial Ph.D. student at DTU, Tommy Riviere Odgaard (Odgaard, Bjarløv, & Rode, n.d.). His work investigated the combination of several measures to cope with the changed hygrothermal conditions as a consequence of the application of interior insulation system. This included hydrophobization of the exterior masonry surface (using Remmers Funcosil FC hydrophobization, with a concentration = ~40% w/w), as well as the implementation of an intentional thermal bridge near the wooden lath, created by installing 100 by 200 mm AAC blocks with higher thermal conductivity, below the wooden floor structure, see picture 4 of Fig. 9.

The experimental set-up was designed around the use of a 40 feet insulated reefer containers, placed at the test site of the Department of Civil Engineering at the Technical University of Denmark in Kgs. Lyngby, Denmark (55.79°N, 12.53°E). For the experiment, 8 holes of 1 m in width and 2 m in height were cut into the west-south-western facade of the container, which would accommodate the masonry assemblies, see Fig. 10. The masonry assemblies were constructed, with the dimensions 198.7 cm high, 94.8 cm wide, and 35.8 cm thick, see Fig. 9. Thickness corresponding to 1½ stones, with a 10 mm layer of rendering on the interior side. Designed to replicate a typical Danish masonry wall built between 1850 to 1930, using yellow soft-moulded bricks, and 7.7% lime adjusted mortar in the joints and for the interior rendering. The masonry assemblies were constructed as a 3-dimensional set-up including a wooden floor structure and a ½-stone adjacent internal masonry wall, rendered on both sides. Carried out to emulate potential problems which could occur due to the thermal bridging effect created by these adjacent elements. Over the course of the experiment, digital HYT 221 sensors (IST, 2014) logged the temperature and relative humidity every 10 minutes, at up to 10 sensor locations within each assembly, see Fig. 9. Additionally, sensors were installed inside and outside of the container for measuring the indoor and outdoor climate conditions. Rain measurements were carried out through rain gauges installed on the exterior side of the container.

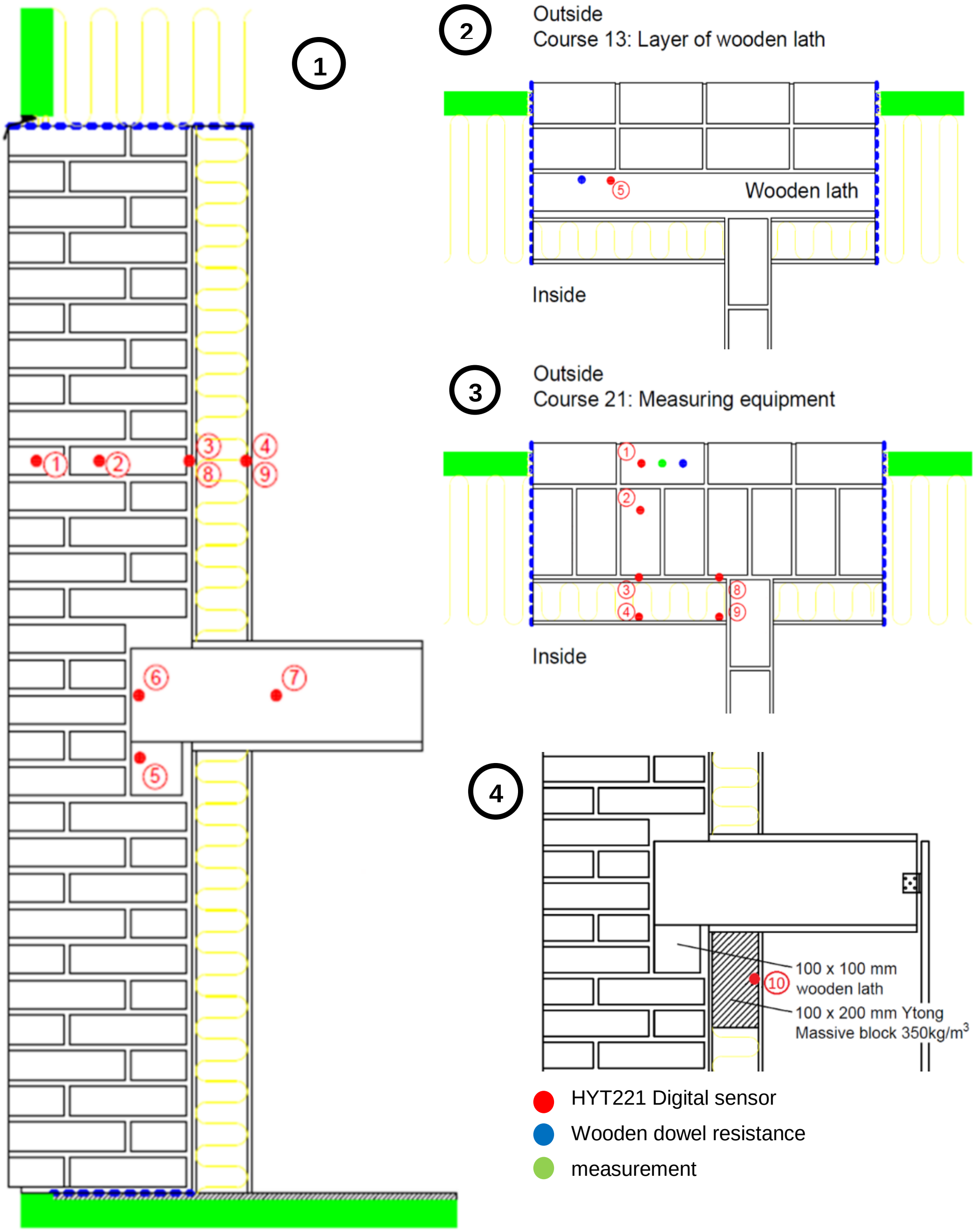


Fig. 9.: Sensor placement. 1) Vertical section showing sensor placement. 2) Horizontal section at masonry course 13 showing sensor placement. 3) Horizontal section at masonry course 21 showing sensor placement. 4) Vertical section showing sensor placement in AAC block below the floor structure

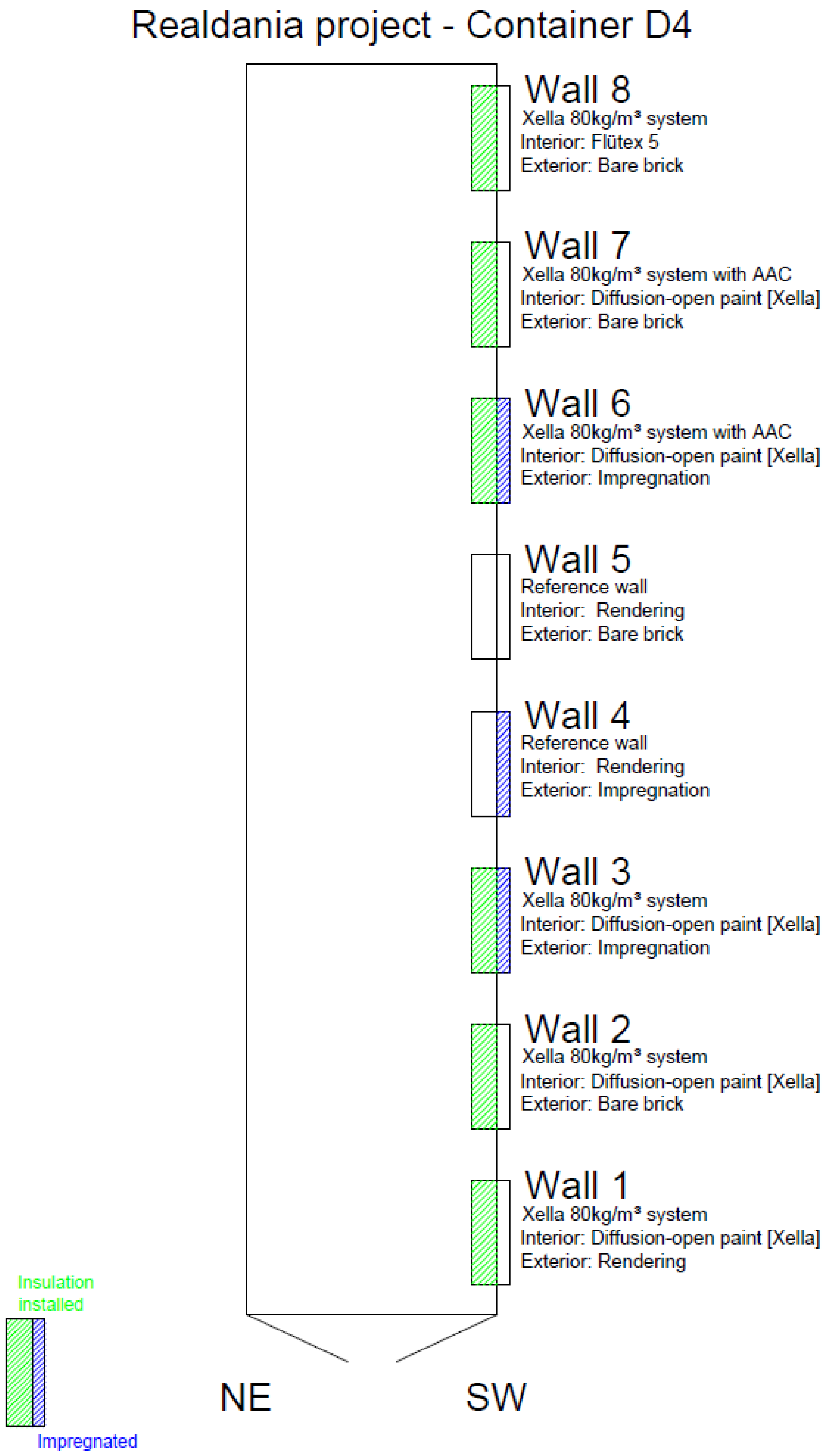


Fig. 10.: Overview of the Realdania container

Prior to the installation of the insulation systems, the masonry assemblies were after their completion on September 18th 2014 subjected to a forced dry-out period (carbonizing process), both internally and externally, which inevitable prolonged the constructed process prior to the installation of the insulation. The external forced dry-out was carried out from primo December 2014 to mid-April 2015. The insulation systems were installed in ultimo February 2015. The experiment was in operation from May 1st 2015 until May 1st 2017, and the temperature and relative humidity of the indoor climate were maintained throughout the year using convectors and humidifiers, ensuring 20°C and 60% relative humidity. Dehumidification and cooling of the indoor climate was not carried out as part of the experimental set-up, and fluctuation due to high humidity or temperature could occur over the course of the experiment.

2.3.2 Intermediate results

The experimental results from the test set-up at DTU indicate that the hydrophobization has varying effect depending on the season. During winter, it limits transport towards the cold exterior climate, leading to high RH levels in the wall. While during summer, the hydrophobization limits transport from the warm moist exterior towards the interior climate, resulting in low relative humidity within the wall structure. This can be seen from Fig. 11 below, where the two hydrophobized walls have high relative humidity during the winter period after the stabilization period. The relative humidity is then reduced greatly during the following summer period, for then to increase to around 100% again in the following winter period. A different tendency is seen for the un-hydrophobized wall, which do not fluctuate greatly during the seasons, but instead maintains a high relative humidity over the entire year. These results collaborate with the simulation results found by Peter Otiv, as well as the transient simulation results by Dysted and Sandholdt.

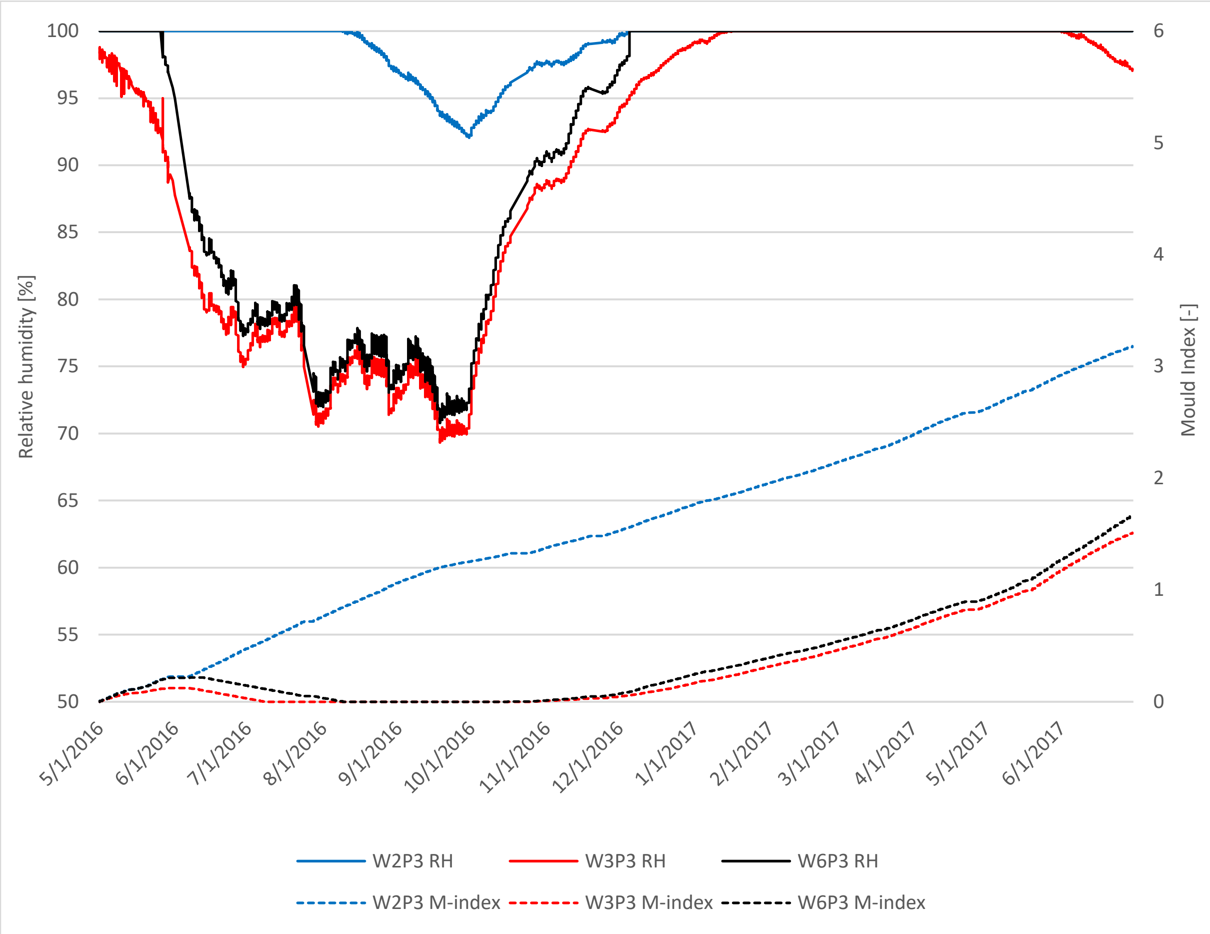


Fig. 11.: Measured relative humidity, calculated mould index at the sensor located at the interface between the masonry wall and the insulation system. (Odgaard, Bjarløv, & Rode, n.d.)

In addition, it was found that the intentional thermal bridge in combination with the hydrophobization on the exterior surface had a positive effect on the wall structure, resulting in a reduction of the relative humidity in the wooden lath, thus lowering the risk of wood decay occurring, calculated according to (Viitanen, et al., 2010). This can be seen from Fig. 12 below, where the interior insulation alone results in an increase in the relative humidity throughout the year. After the application of the hydrophobization on the exterior surface, the relative humidity is then reduced below the reference wall, and by installing the intentional thermal bridge, the relative humidity is then reduced even further. A similar trend is seen for the wooden beam end, however with the exception that the hydrophobized walls show an increase in the relative humidity during the winter period, as seen for the un-hydrophobized walls, see Fig. 13.

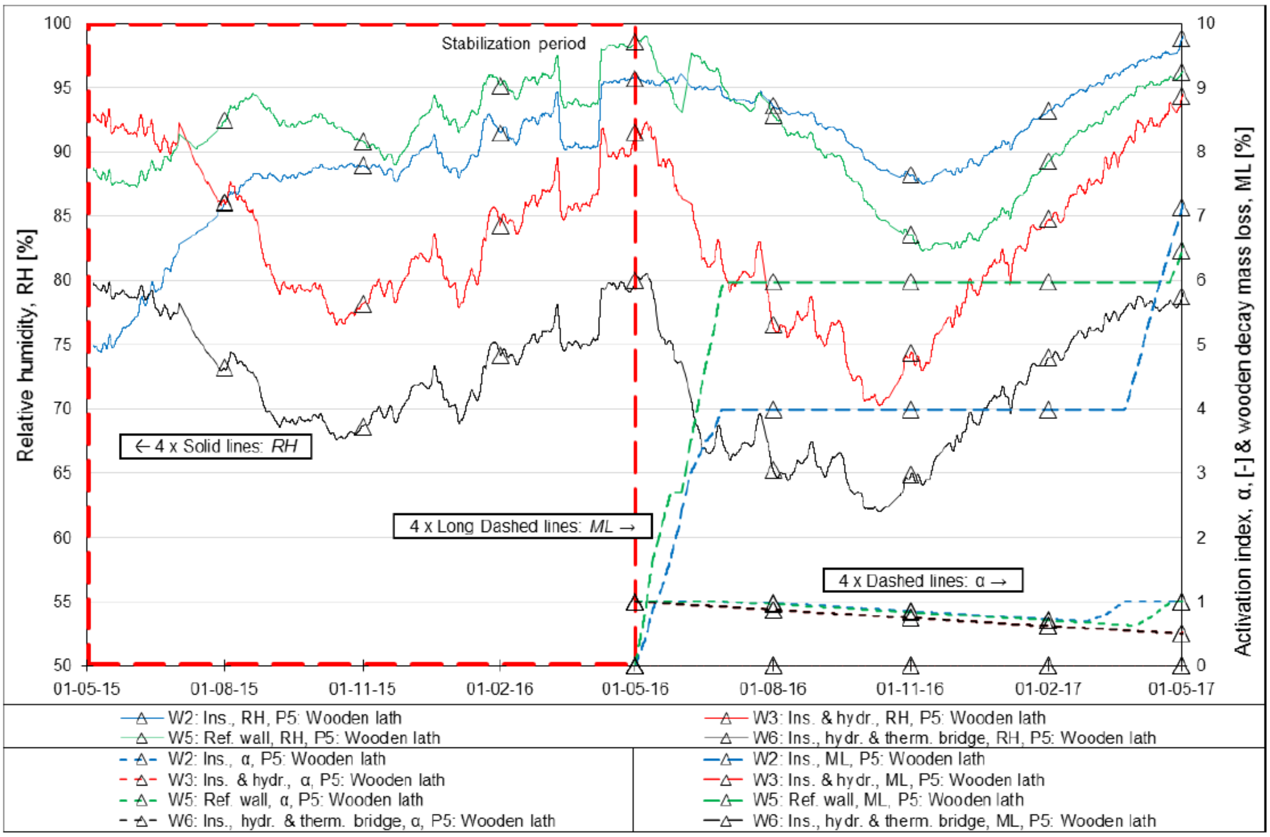


Fig. 12.: Measured relative humidity, calculated activation and mass loss at the sensor located in the wooden lath. (Odgaard, Bjarløv, & Rode, n.d.)

Regarding mould growth, calculated according to (Ojanen, et al., 2011), the results indicated that although the intentional thermal bridge in combination with the hydrophobization is seen to reduce the relative humidity enough to greatly lower the risk of wood decay. It was seen that a risk of mould growth might occur at the interface between the masonry wall and the insulation system, as seen in Fig. 11.Fig. 13.: The un- hydrophobizated, interior insulated wall showed a mould index value of approximately 3.2 after the first 14 months (on July 1st 2016), while the two hydrophobized walls showed a mould index value of approximately 1.5-1.6. It has however been suggested that a reduction of the moisture content of the indoor climate, e.g. through the use of mechanical ventilation with humidity control, could be the solution to this issue, as a rather high indoor relative humidity of 60% was used over the course of the experiment (Odgaard, Bjarløv, & Rode, n.d.).

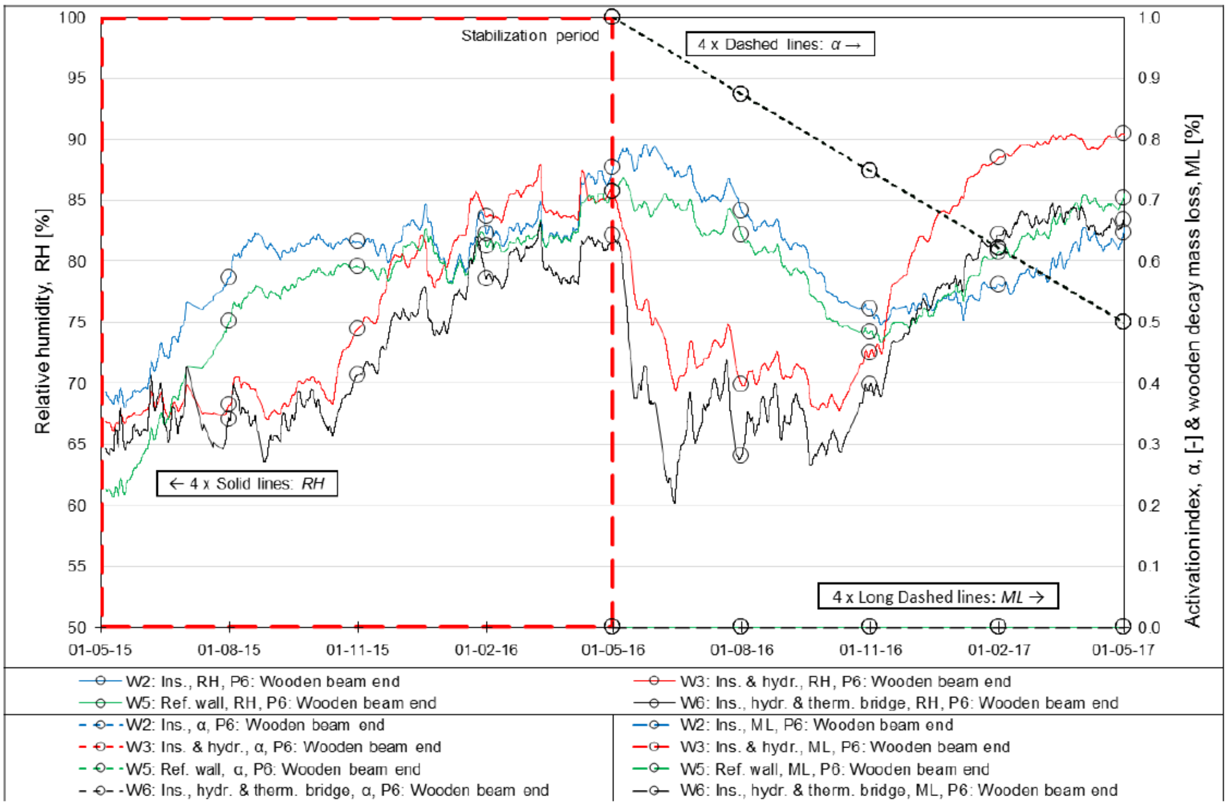


Fig. 13.: Measured relative humidity, calculated activation and mass loss at the sensor located in the wooden beam end. (Odgaard, Bjarløv, & Rode, n.d.)

2.4 Undersøgelse af robusthed af indvendig isolering (Investigation of robustness of interior insulation)

2.4.1 Project description

Results and figures presented below are from the bachelor's thesis by former BSc. students at DTU, Jonas Skov Jacobsen and Kent Helmann Dabelsteen (Jacobsen & Dabelsteen, 2016). Their work investigated the robustness of interior insulation systems, hereunder the Multipor system. In addition, a microclimate investigation was carried out for the hygrothermal conditions between interior insulated walls and items placed in close proximity. The investigation included four tests, of which only the microclimate investigation will be presented in this chapter, while the remaining three will be presented in the following chapter.

- Microclimate test: 25 x 25 cm acrylic glass plates and leather (synthetic) patches were mounted on the interior surface of the walls to emulate the effect of placing heavy leather furniture and picture frames directly up against/on the interior surfaces. Suspected to create a microclimate with higher risk of mould growth, between these elements and the interior surface of the masonry assemblies. The acrylic glass plates were mounted with 15 mm to the interior surface, while the leather patches were mounted directly against the surface, both with sensors installed between the elements and the wall surfaces. The acrylic glass plates were furthermore assessed against three different exterior surface treatments (rendered, un-hydrophobized and hydrophobized), while the leather patches were only assessed against two treatments (un-hydrophobized and hydrophobized). The results were evaluated using the Isopleth diagram (Sedlbauer, 2012) for mould prediction. The microclimate conditions were measured in the period 24.03.2016 – 27.05.2016.

2.4.2 Intermediate results

- Microclimate test:

  From the microclimate test, it was found that the leather patches mounted directly on the wall would result in higher relative humidity in comparison to the acrylic glass place (installed 15 mm from the wall surface), as shown in picture 1 of Fig. 14 The comparison between the two different types of microclimates also showed a higher relative humidity between the acrylic glass plate and the hydrophobized wall, in comparison to the un-hydrophobized wall. The opposite was the case for the relative humidity between the leather patches and the walls, where the un-hydrophobized wall showed higher relative humidity. The comparison between the three exterior surface treatments (with the acrylic plates installed), showed similar results for the render and the un-hydrophobized walls, slightly lower than the hydrophobized wall by 3-4%, as shown in picture 2 of Fig. 14.

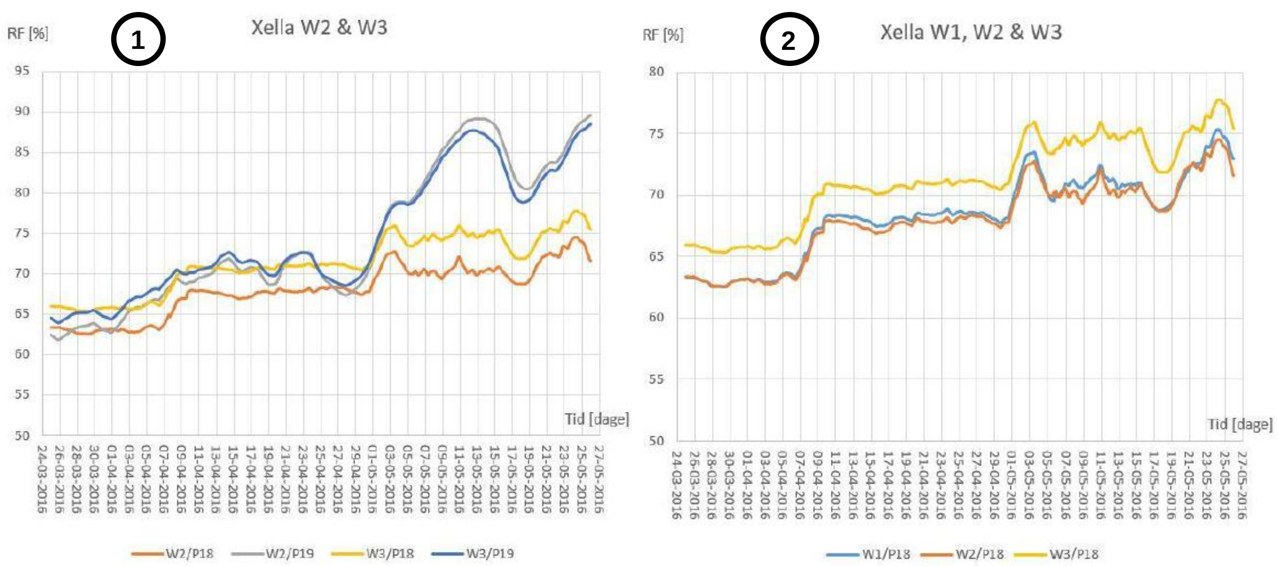


Fig. 14.: Microclimate measurements. 1) Comparison between the leather patches (grey and blue) and the acrylic plates (orange and yellow). (Yellow and blue is hydrophobized, and orange and grey are un-hydrophobized). 2) Comparison between the different surface treatments (rendered=blue, un-hydrophoized=orange, and hydrophoized=yellow)

The Isopleth diagram did not predict risk of mould growth between the acrylic glass plates and the reference wall or the render-, un-hydrophobized- or hydrophobized wall with interior insulation see Fig. 15 and Fig. 16. However, the diagram did predict a risk for the both the un-hydrophobized- and hydrophobized wall with the leather patches, see Fig. 17. It was therefore concluded that heavy furniture should not be place directly up against the interior surface, while picture frames hanging on the walls would not cause moisture related issues. In addition, the difference between the relative humidity measured for the microclimate behind the acrylic glass plates and the leather patches, could raise questions. As the leather patches were mounted directly on the interior surfaces (greatly limiting the air flow between wall and leather), while the acrylic glass plates were installed with a distance of 15 mm to the interior surface, thus creating a considerably difference environment to that located between the leather patches.

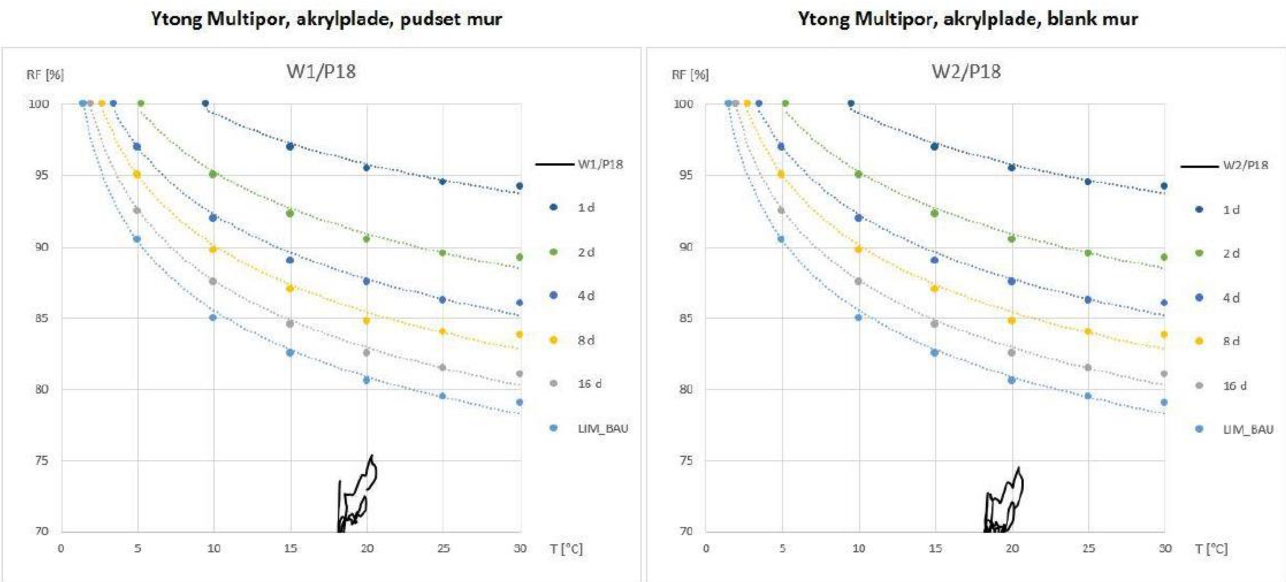


Fig. 15.: Isopleth diagram for the microclimate. 1) The rendered Multipor wall with acrylic plate. 2) The un-hydrophobized Multipor wall with acrylic plate.

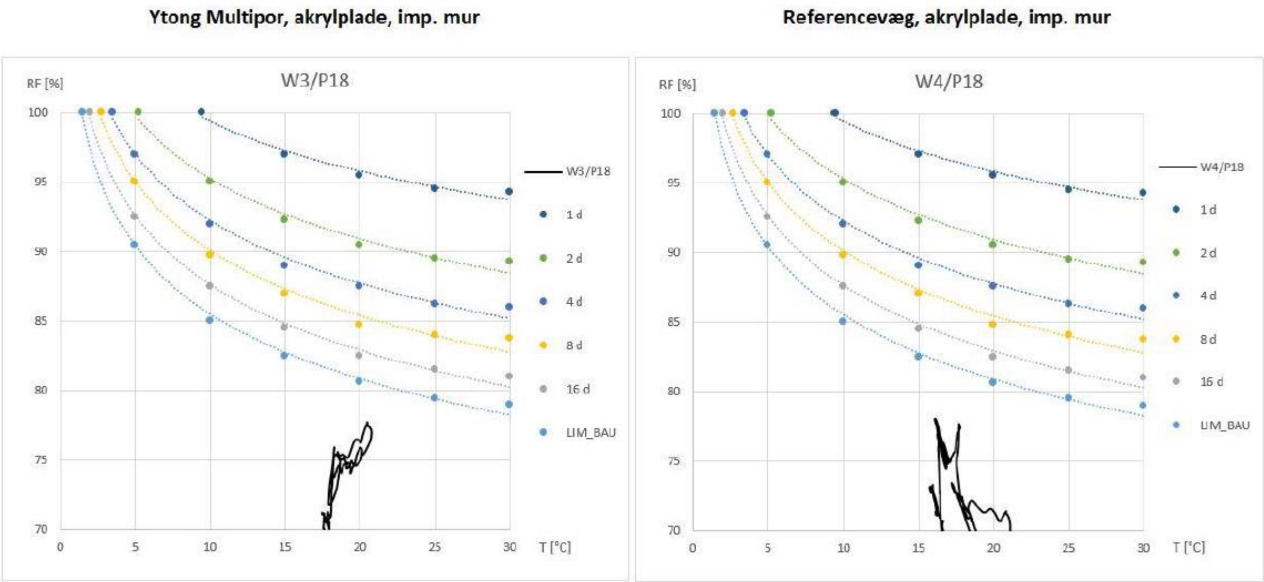


Fig. 16.: Isopleth diagram for the microclimate. 1) The hydrophobized Multipor wall with acrylic plate. 2) The hydrophobized reference wall with acrylic plate.

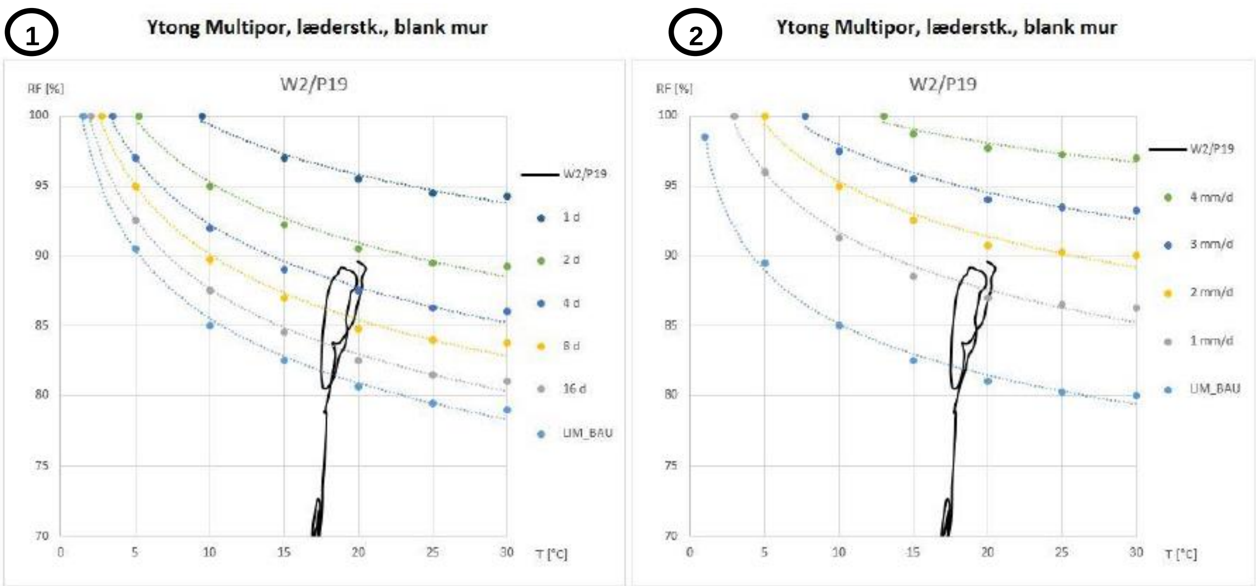


Fig. 17.: Isopleth diagram for the microclimate, for the un-hydrophobized Multipor wall.

Unfortunately, the microclimate test did not include data from “un-covered“ sensors installed on the interior surface of the respective walls, which could serve as reference cases. This could have proved beneficial to determine the actual effect of the acrylic plates and the leather patches, in comparison to the conditions on the same respective wall surfaces without these elements installed.

2.5 Hygrothermal modelling of internal insulation to solid masonry walls, with lowered interior relative humidity

2.5.1 Project description

Results and figures presented below are from a simulation study carried out by Ph.D. student at DTU, Nickolaj Feldt Jensen. For the study, the validated 1-D hygrothermal simulation models created by Peter Otiv (Otiv, 2016) (described in section 2.2), were modified so the relative humidity of the indoor climate was lowered to 40%, in comparison to the original 60%. While the original indoor relative humidity of 60% is a traditional used set point used in experiments for indoor climate experiments in Denmark (Hansen & Møller, 2016), a set point of 40% seem appropriate for the more common conditions in residential buildings, normally ranging between 30 and 50% during the winter months (Brandt, 2013). The purpose of the study was to investigate the effect of lowering the relative humidity of the indoor climate on the hygrothermal conditions at sensor locations 2 and 3 within the wall structure (roughly corresponding to the location of the wooden beam end, and the interface). As described in section 2.2, one of the wall models was simulated with a hydrophobized treatment on the exterior surface, and the other model as an un-hydrophobized brick wall. All models were simulated using the measured exterior climate data from DTU's test site, as the exterior boundary conditions. Lastly, the simulation results were assessed using Delphin built-in VTT mould prediction model (Ojanen, et al., 2011).

2.5.2 Intermediate results

The simulated relative humidity for point 1 (near the exterior surface) in both the un-hydrophobized wall and hydrophobized wall, showed little to no change, as an effect of the lowered relative humidity in the indoor climate, see Fig. 18 and Fig. 19. For the un-hydrophobized wall with an interior relative humidity of 40%, the relative humidity in point 1 is rather stable around 98-100% during the winter period, while fluctuating greatly during the summer and autumn periods. The hydrophobized wall, peaks around 93% during start January, and has low peaks of around 40% over the course of the summer.

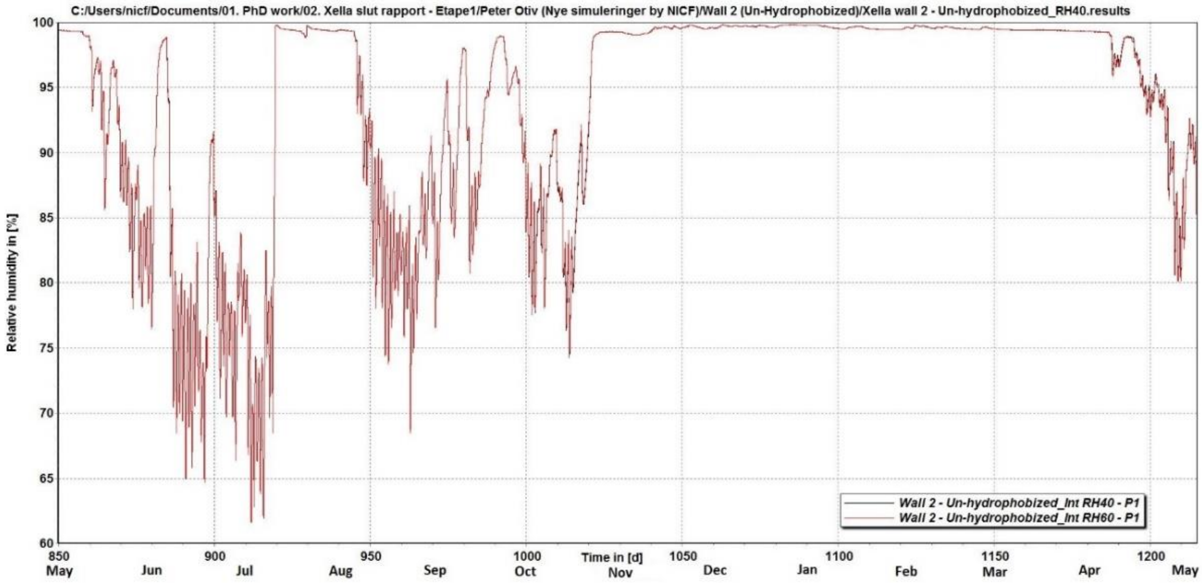


Fig. 18.: Simulated relative humidity for point 1, in the un-hydrophobized wall with 40% interior relative humidity (black) and 60% interior relative humidity (red).

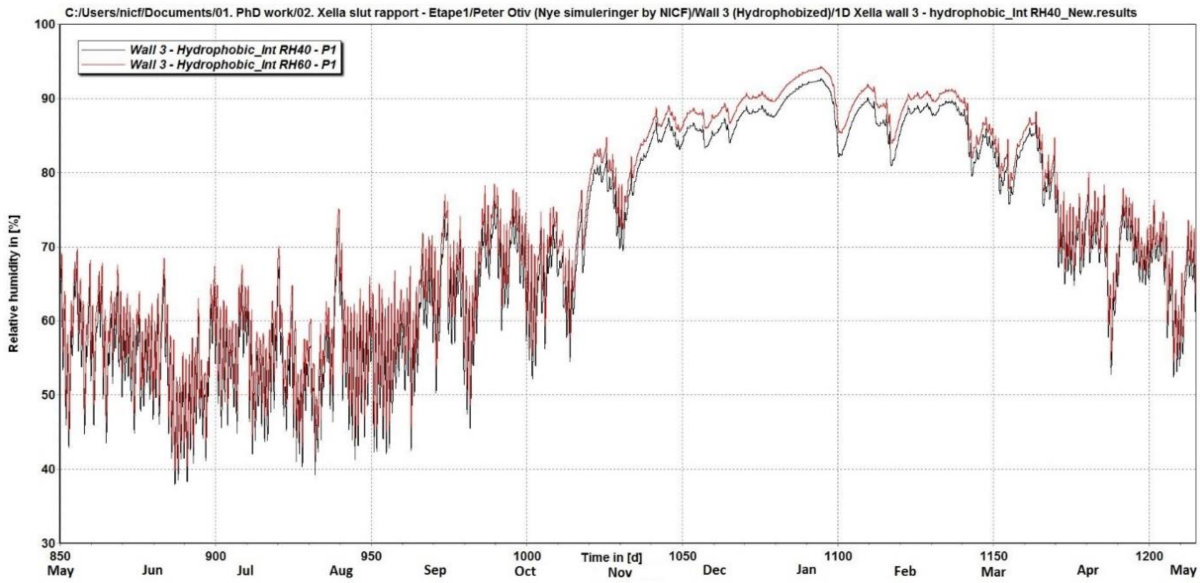


Fig. 19.: Simulated relative humidity for point 1, in the hydrophobized wall with 40% interior relative humidity (black) and 60% interior relative humidity (red).

The simulated relative humidity for point 2 (middle of masonry wall) showed only a small reduction during the winter period for the un-hydrophobized wall, for about one month, see Fig. 20, while the hydrophobized wall showed 5-10% reduction over the course of the year due to the lowered indoor relative humidity, see Fig. 21. The largest reduction in the relative humidity occurs during the summer period (May to October). For the un-hydrophobized wall (interior RH of 40%), the relative humidity in point 2 is rather stable around 98-100%, with load peak down to 96% in late November. The hydrophobized wall, peaks around 85% during late February, and has low peaks down to around 45% over the course of the summer.

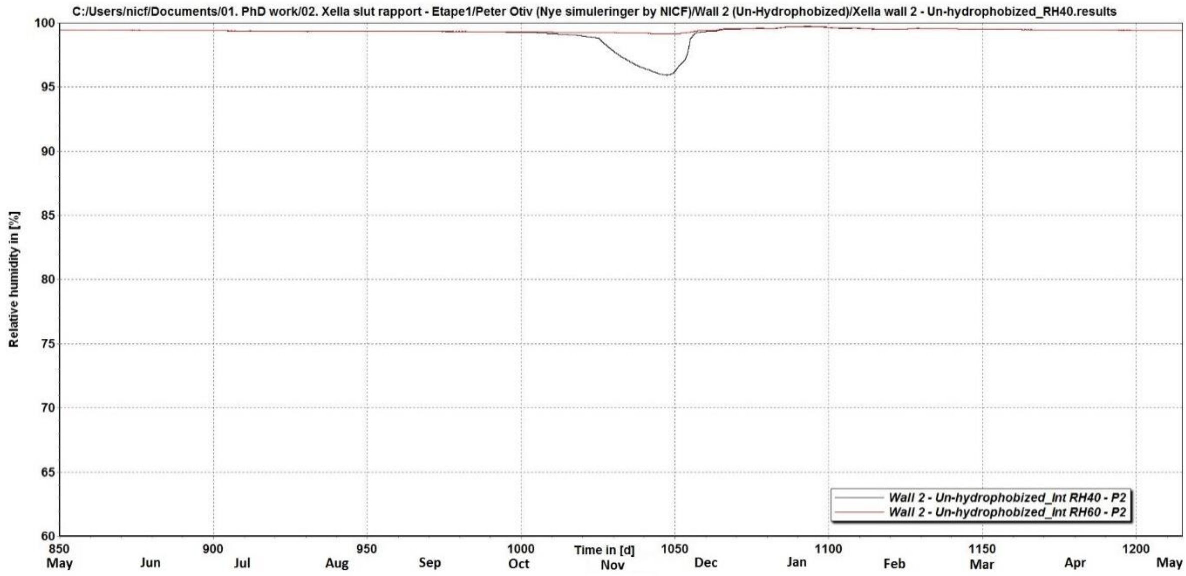


Fig. 20.: Simulated relative humidity for point 2, in the un-hydrophobized wall with 40% interior relative humidity (black) and 60% interior relative humidity (red).

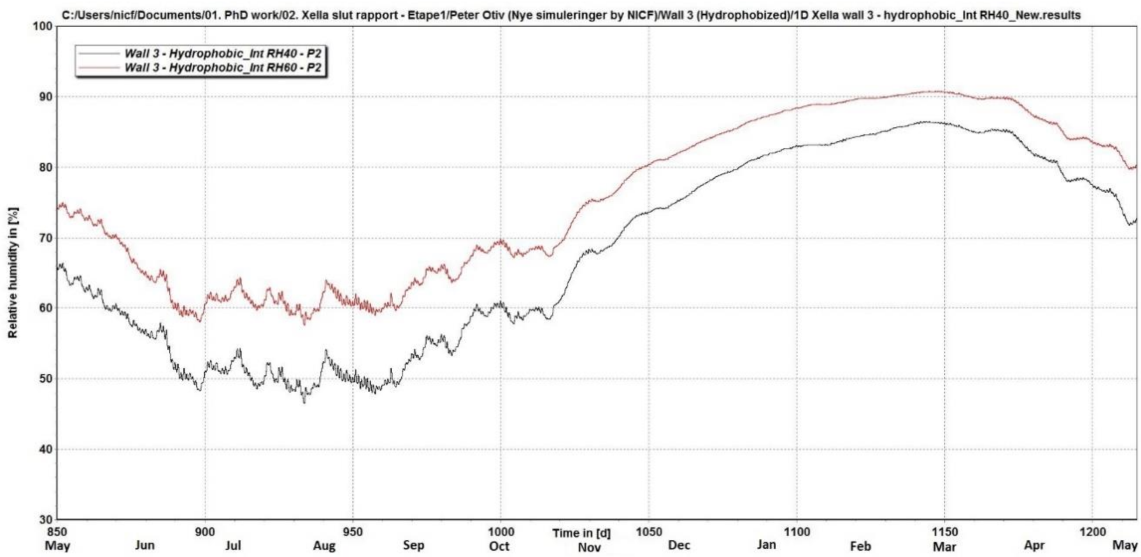


Fig. 21.: Simulated relative humidity for point 2, in the hydrophobized wall with 40% interior relative humidity (black) and 60% interior relative humidity (red).

The simulated relative humidity for point 3 (interface between masonry wall and insulation) in the un-hydrophobized wall showed little to no reduction during the winter and spring period (February to June) due to the lowered indoor relative humidity, see Fig. 22. However, during the summer and autumn period (July to December) a difference of up to 20% was seen. For the hydrophobized wall, a difference of 10-20% was seen for the relative humidity over the course of the year, see Fig. 23. The largest difference was seen during the summer period, while the smallest difference is seen during the winter. For the un-hydrophobized wall (interior RH of 40%), the relative humidity in point 3 peaks around 96-98% over the winter period, and has a low peak around 71% in start September. The hydrophobized wall, peaks around 87% between March and April, and has a low peak of around 42% in September.

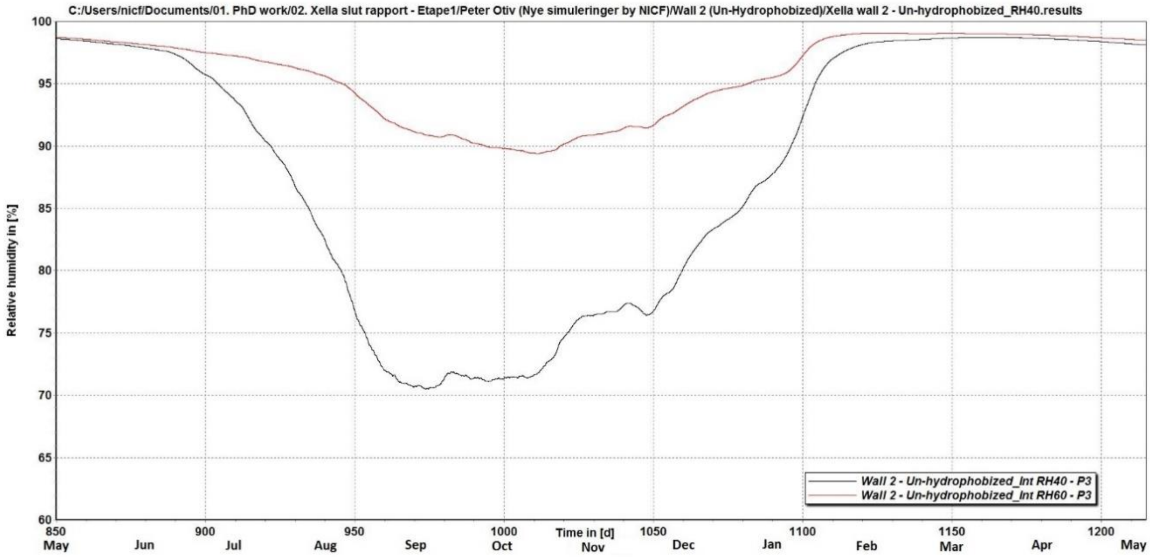


Fig. 22.: Simulated relative humidity for point 3, in the un-hydrophobized wall with 40% interior relative humidity (black) and 60% interior relative humidity (red).

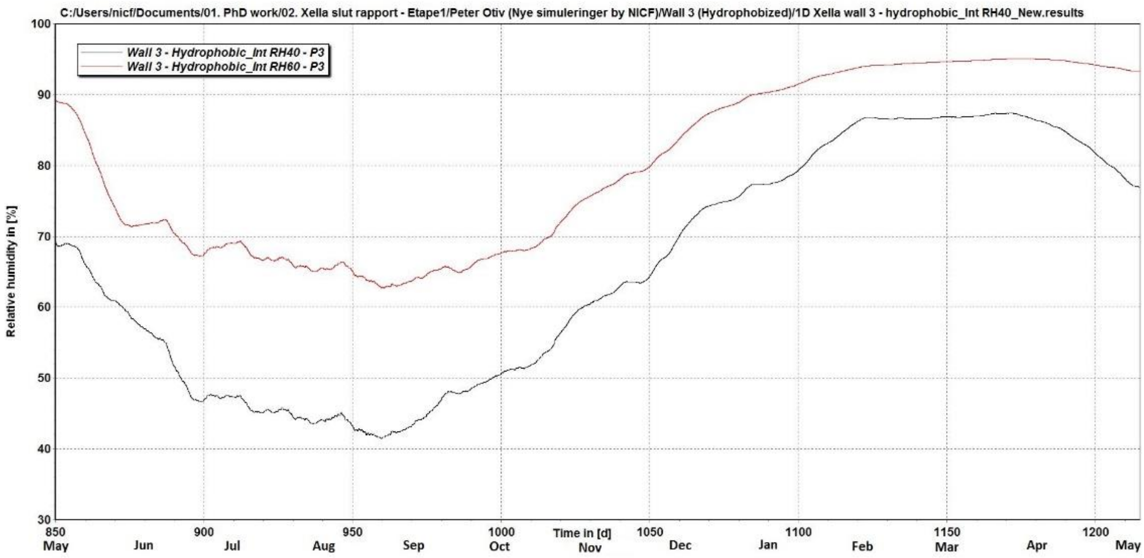


Fig. 23.: Simulated relative humidity for point 3, in the hydrophobized wall with 40% interior relative humidity (black) and 60% interior relative humidity (red).

The simulated relative humidity for point 4 (interior surface), showed for both the un-hydrophobized and the hydrophobized wall, a reduction of the relative humidity at the interior surface between 10-30%, see Fig. 24 and Fig. 25. Common for both walls is that at 40% indoor relative humidity, the relative humidity at the interior surface becomes more stable in comparison to 60% indoor relative humidity, where more fluctuations are seen over the course of the year. For the un-hydrophobized wall (interior RH of 40%), the relative humidity in point 4 peaks around 50-55% during the spring period, and has low peaks around 45% during autumn and winter. The hydrophobized wall is rather stable around 40-45% over the course of the year.

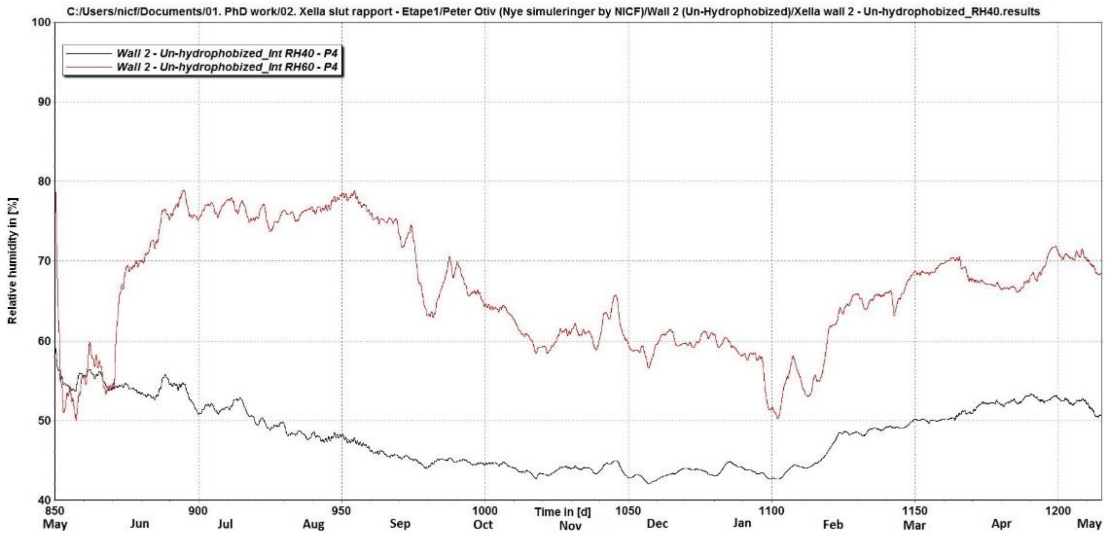


Fig. 24.: Simulated relative humidity for point 4, in the un-hydrophobized wall with 40% interior relative humidity (black) and 60% interior relative humidity (red).

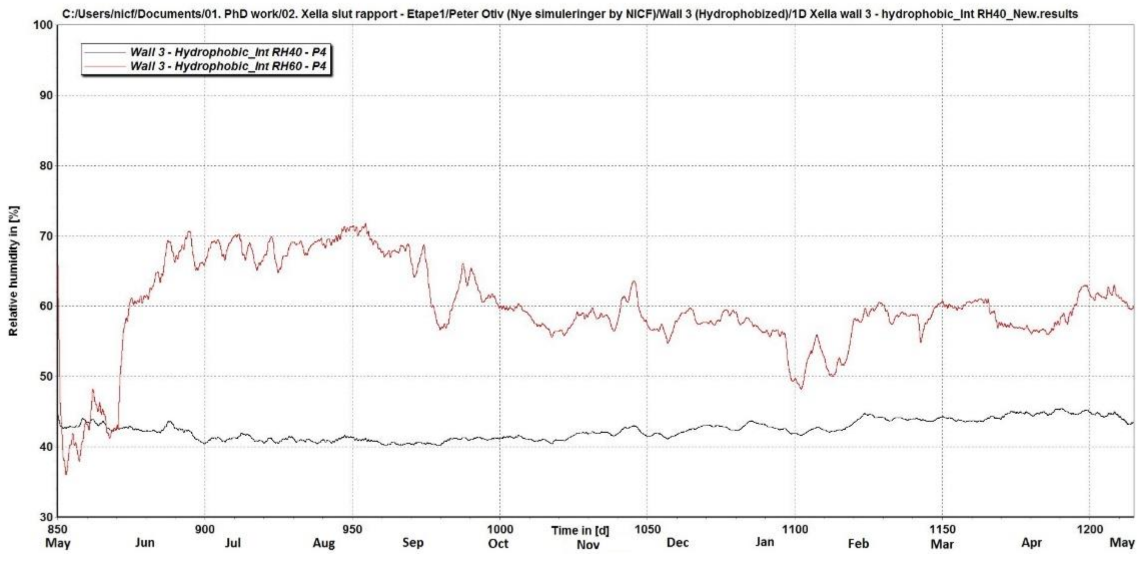


Fig. 25.: Simulated relative humidity for point 4, in the hydrophobized wall with 40% interior relative humidity (black) and 60% interior relative humidity (red).

The results from the small simulation study suggest that with a lowered interior relative humidity of 40%, it might be possible to maintain a mould index value within the acceptable limit. As seen from Fig. 26, both the un-hydrophobized and the hydrophobized wall maintain a mould index value below 1 over the course of the third simulated year. Comparing the simulation results to the experimental results by Tommy Odgaard, it can be seen that while the simulated results for the hydrophobized wall is only slightly lower than the experimental results (mould index value of 0.4 and 0.9 respectively, per May 1st 2016). The simulated results for the un-hydrophobized wall is considerably lower than the experimental results (mould index value of 0.7 and 2.6 respective, per May 1st 2016). The simulation results therefore suggest that the interior climate does in fact play an important role regarding the hygrothermal conditions in the test walls, and that a lowering of the interior relative humidity to 40% could potentially lower the risk of mould growth to an acceptable level.

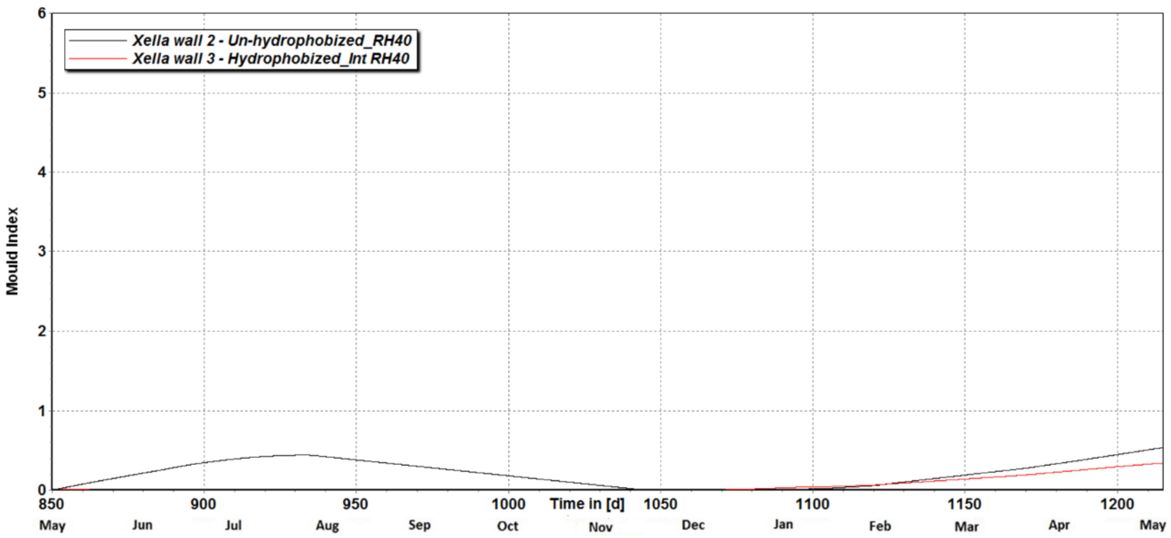


Fig. 26.: Calculated mould index at the interface for the third simulated year (May 2015 to May 2016), based on the simulations using an interior relative humidity of 40%. Un-hydrophobized wall (black) and hydrophobized wall (red).

3. Robustness and surface treatments

3.1 Undersøgelse af robusthed af indvendig isolering (Investigation of robustness of interior insulation)

3.1.1 Project description

Results and figures presented below are the robustness and surface treatment tests from the bachelor's thesis by former BSc. students at DTU, Jonas Skov Jacobsen and Kent Helmann Dabelsteen (Jacobsen & Dabelsteen, 2016). The investigation included the following tests:

- Cup test, where the vapour permeability of Flügger Flutex 5 were assessed, in order to determine the consequence of applying single and multiple layers of diffusion-tight paint on the interior surface of diffusion-open insulation systems. As it was theorized that enough paint layers could limit the vapour diffusion to the indoor climate, similar to the effect of a vapour retarder. The cup test was carried out according to EN ISO 12572:2001. A total of 12 gypsum samples were tested, consisting of 4 different sample variations (raw gypsum board, with 4 paint layers, with 7 paint layers, and with 10 paint layers). The paint layers were applied with a wet-film thickness of 120-125 µm. The samples were tested using the salt solution KNO_3 establishing a relative humidity level of 94%.

- Hard body impact test, where metal balls of different size and weight (1.070 and 2.873 kg) were used to determine if the insulation systems could withstand blows, see picture 1 of Fig. 27. The test was carried out to simulate blows caused by occupants or items during the operational phase of the building. The hard body impact test was based on ISO 7892:2012 'Vertical building elements – Impact resistance tests – Impact bodies and general test procedures', and European Standard ETAG 004. For the impact test with 10 Joule, the test was carried out with both metal balls, to determine influence of the ball size. Following each hit by the metal ball, measurements were taken for the width, height and depth of the area of impact.

- Withdrawal and displacement test, where the load carrying capabilities were assessed for seven different wall plugs, mounted on the interior surface of the wall structure. The following plug types were tested: Würth's gypsum plug, common rawlplug, 50 mm Fischer FID 50 plug, 100 mm Fischer FID 90 plug, 50 mm Ytong Spiraldübel, 85 mm Ytong Spiraldübel, and Ytong Flatnail. The test was divided into two parts 1) Withdrawal test, where a 300mm shelf was mounted to the plugs, with an acrylic plate installed below to obtain an almost direct withdrawal effect, see picture 2 of Fig. 27. 2) Displacement test, where the plugs were mounted directly into the insulation system and the weights were hanging in a steel wire, see picture 3 of Fig. 27. Over the course of the experiment, the load carrying capabilities of the plugs would be assessed by adding 1000g weights, until a max load of 30kg or until the fixture broke loose from the wall surface.

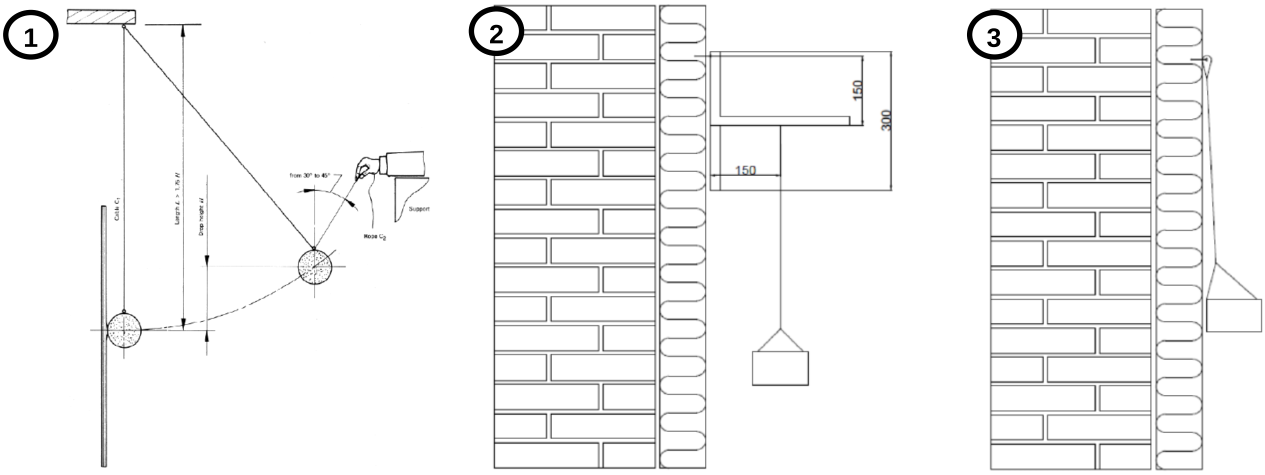


Fig. 27.: Test set-ups: 1) Hard body impact test. 2) Withdrawal test. 3) Displacement test.

3.1.2 Intermediate results

The results for each of the four tests are presented below:

- Cup test:

  From the cup test, the following Z and S_d values were obtained:

  Table 5: Cup test results

	4 paint layers	7 paint layers	10 paint layers
Z [(s·m^2·GPa)/kg]	0.79	0.88	1.32
S_d [m]	0.16	0.18	0.26

According to information provided by Xella Denmark A/S, the Multipor insulation system should not exceed a tightness of more than 25 in Z-value or 4.9 in S_d-value. Based on the obtained S_d-value of 0.16 m for 4 paint layers, it would require 123 layers of paint to exceed this limit. This corresponds well with the information provided by Xella Denmark A/S, stating a maximum of 100 paint layers. However, a fault was found in the experimental process, related to the application of the paint layers. According to the industry organization “Danske Malermestre” the common paint layer thickness is 120-125 µm, dry-film, while in the bachelor project the paint layers were applied with a thickness of 120-125 µm, wet-film. The above-mentioned results are therefore the S_d-values for paint layers slightly thinner than the industry standard, thus increasing the amount of paint layers before exceeding the limit stated by Xella Denmark A/S. Taking this into account, the 100 paint layers specified by Xella sounds reasonable.

- Hard body impact test:

  Regarding the influence of the ball size, the test showed that while the larger ball would hit a hole into the wall (keeping the finish layer still on the wall), the smaller ball would break off the finishing layer. However, after scratching out the finishing layer for the test with the larger ball, it was found that the hole depth from the two balls were quite similar. Furthermore, the break diameter was shown to be almost identical for the two ball sizes. This indicated that the impact test could be carried out using either ball weight, as long as the drop height of the ball would be adjusted to result in an impact force of 10 joule. From the hard body impact test with an impact force of 10 and 3 Joule, the following results were obtained. From Table 5 it is seen, that both hole diameter and crack depth increases with increasing hits on the Multipor system, and that crack depth for the 10 and 3 Joule balls quite similar.

Table 6: Hard body impact test results

Test	10 Joule 1st hit	10 Joule 2nd hit	10 Joule 3rd hit	3 Joule 1st hit	3 Joule 2nd hit	3 Joule 3rd hit
Diameter x [mm]	42	60	64	19	30	36
Diameter y [mm]	42	50	61	18	28	33
Max crack depth [mm]	0.4	1.5	2.5	0.1	1.5	2.5 <

The Multipor system is using a light-mortar in combination with a reinforcement mesh as finishing layer, to protect the porous insulation material. After impact test, the light-mortar and reinforcement mesh at the places of impact were removed, to assess the damage to the insulation material. While the 3 Joule hits did not show signs of damage to the insulation material, the 10 Joule hits did show signs of damage to the inner most part of the insulation material. The conclusion for the hard body impact test was that the performance of the Multipor system was at acceptable level for indoor use.

- Withdrawal and displacement test:

  From the Withdrawal and displacement test, the following loads were determined for plug types:

Table 7: Withdrawal and displacement results

Withdrawal							
Plug type	Würth gypsum plug	Rawlplug	Fischer FID 50	Fischer FID 90	Ytong Spiraldübel 50mm	Ytong Spiraldübel 85mm	Ytong Flatnail
Load [kg]	14	7	15	30	13	8	12
Displacement							
Plug type	Würth gypsum plug	Rawlplug	Fischer FID 50	Fischer FID 90	Ytong Spiraldübel 50mm	Ytong Spiraldübel 85mm	Ytong Flatnail
Load [kg]	14	8	16	27	18	23	25

The results indicate that the larger and wider plug types such as Fischer FID 90 and Ytong Spiraldübel 85 mm performs better when mounted on the Multipor interior insulation system, in comparison to the smaller and thinner rawlplug and Würth gypsum plug. The Fischer FID 90 plug showed good load carrying capabilities in both tests, while Ytong Spiraldübel 85 and the Ytong Flatnail, showed good load carrying capabilities for the displacement test, but poor performance for the withdrawal test. An interesting finding was that the test of the 50 and 85 mm Ytong Spiraldübel, indicated that the 50 mm would perform better at the withdrawal test than the 85 mm. While the opposite was true for the displacement test. The general conclusion was that the Multipor performed well with regards to the displacement test, but poorly in the withdrawal test due to the porosity of the material.
It should be noted that although the experimental results from the withdrawal test are correct, the calculated momentums for the test are incorrect. The momentums were calculated by Jacobsen and Dabelsteen based on point load, while it should have been calculated as line load.

4. Results

This section summarises the intermediate results from the two previous chapters.

4.1 Mould growth and other moisture related issues

- Hydrophobization of the exterior surface reduces the moisture content in the masonry during the summer period, but the moisture then increases during the following winter period. These results are based on high indoor relative humidity (60%), which may be considered relatively high.
- The intentional thermal bridge installed in front of the embedded wooden elements showed success in reducing the moisture content in the wooden elements to greatly lowering the risk of wood decay.
- At the interface between the masonry wall and the insulation system (sensor 3), the hydrophobized wall, as well as the hydrophobized with the intentional thermal bridge, showed lower relative humidity in comparison to the un-hydrophobized wall. The un-hydrophobized wall maintained rather high relative humidity levels over the course of the year. While both hydrophobized walls showing relative humidity levels around 70-80% during late summer and autumn periods, and high relative humidity levels, similar to those of the un-hydrophobized wall, during the winter period. Additionally, it was seen that after the first 14 months after the stabilization period, the mould index at the interface reached 3.2 and 1.5-1.6 for the un-hydrophobized wall and the hydrophobized walls, respectively.
- The hygrothermal simulations using an indoor relative humidity of 40% showed:
    - ➢ Almost no change in the relative humidity at the exterior surface, as an effect of the lowered indoor relative humidity.
    - ➢ At the middle of the masonry wall, the un-hydrophobized wall experienced high relative humidity levels (95-100%). The hydrophobized wall ranged between 50 and 85%, of which the relative humidity was over 80% from mid-December to start April.
    - ➢ At the interface, the un-hydrophobized wall experienced high relative humidity levels (97-100%) from February to June, while the relative humidity decreased to around 70-75% during the summer. The hydrophobized wall ranged between 45 and 87%, of which the relative humidity is over 80% from mid-January to late April.
    - ➢ For the interior surface, the un-hydrophobized wall ranged between 40 and 60% over the course of the year, while the hydrophobized wall was rather stable around 40-45%.
    - ➢ The results showed a lowered mould index value for both the un-hydrophobized and the hydrophobized wall as an effect of lowering the interior relative humidity to 40%, in comparison to the 60% in the experimental set-up.
- Microclimatic measurements using acrylic plates and leather patches showed:
    - ➢ That the leather patches mounted directly on the wall would result in higher relative humidity in comparison to the acrylic glass place. The sensors behind the

leather patches peaked at around 85-90% in the summer (both walls showed relatively similar results), while the sensors behind the acrylic plates were more stable at around 70-80%.

- A higher relative humidity was observed between the acrylic glass plate and the hydrophobized wall (72-78% over the summer), in comparison to the un-hydrophobized wall 69-75% over the summer). The opposite was the case for the relative humidity between the leather patches, however, the difference between the walls were quite small.
- The rendered- and the un-hydrophobized wall showed relatively similar results, both 3-4% lower than the hydrophobized wall.
- The Isopleth diagram did not predict risk of mould growth behind the acrylic plates, no matter the type of exterior treatment, while the diagram did predict a risk for the leather patches installed on both the un-hydrophobized- and hydrophobized wall.

4.2 Robustness of the insulation system

- The Hard body impact test on the Multipor insulation system, showed little to no damage on the insulation material behind the interior render and reinforcement mesh after the 3 Joule hits, while the insulation material showed sign of damage after the 10 Joule hits.
- The withdrawal and displacement test showed that several of the larger and wider plug types were able to carry loads of up 20-30 kg. Most plug types showed better performance in the displacement test in comparison to the withdrawal test. The Fischer FID 90 plug showed the highest overall load carrying capacity, while the typical Rawlplug showed the lowest overall load carrying capacity.

4.3 Surface treatments

- Regarding the effect of diffusion-tight paint, both Dysted and Sandholdt as well as Jacobsen and Dabelsteen, carried out cup tests in order to determine the vapour resistance. However, the results from the two studies vary greatly. Dysted and Sandholdt created an equation for the application of Flügger Flutex 5 in which $Z = 0.59 \cdot n + 0.55$ $[(s \cdot m^2 \cdot GPa)/kg]$, where n is the number of paint layers. This corresponds to 42 paint layers before exceeding the limit of $Z = 25$ $[(s \cdot m^2 \cdot GPa)/kg]$. Jacobsen and Dabelsteen found that each paint layer would have a $Z = 0.19$ $[(s \cdot m^2 \cdot GPa)/kg]$, corresponding to 123 paint layers before exceeding the limit. However, Jacobsen and Dabelsteen did note that an error had occurred during the execution of the paint layer, in which the paint layer thickness became thinner than intended. Thus increasing the number of paint layer before exceeding the limit. The actual number is therefore lower than the 123 layers.

5. Indications

5.1 General indications for interior insulation of solid masonry walls

5.1.1 Risk of mould growth and other moisture related issues

Based on the current experimental results and simulations, the following indications have been noticed when interior insulation without vapour barrier has been applied to solid masonry walls:

- The installation of an intentional thermal bridge in front of the embedded wooden elements showed a positive effect, as the moisture content in the wooden elements were lowered considerably.
- The hydrophobization treatment of the exterior surfaces seem to have both a positive and a negative effect on the hygrothermal conditions in the wall construction. As the hydrophobization prevents moisture from entering the construction from the warm, moisture exterior in the summer period, resulting in low relative humidity during the summer. However, it also prevents moisture inside the construction from evaporating to cold, dry exterior during the winter period, resulting in high relative humidity during winter. It could therefore be questioned, if the hydrophobization treatment used in the experiment was too tight, and if the use of a less tight treatment would allow the moisture inside the construction to evaporating to the exterior, resulting in lower relative humidity levels during the cold periods.
- A combination of hydrophobization of the exterior surface and lowered indoor moisture content (e.g. similar to the climate class 2 according to EN ISO 13788, an interior moisture addition of 2-4 g/m^3), could further lower the level of relative humidity at the critical interface between the masonry and the insulation system. The hygrothermal simulation results carried out by DTU in December 2017, using an indoor relative humidity of 40%, supports this theory. The simulations indicate that although the indoor relative humidity is lowered to 40%, the relative humidity levels at the interface would still exceed 80% for an extended period of time. The use of another, less tight, hydrophobization could lead to a result below 80% relative humidity. However, the assessment of the hygrothermal conditions using the VTT mould prediction tool indicated that the lowering of the interior relative humidity to 40% would have a large impact on the risk of mould growth. As the mould index was reduced to less than half during the simulated third year for the hydrophobized wall, and to less than one-third for the un-hydrophobized wall.
- Microclimatic experiment indicated that heavy furniture (emulated by the leather patches) should not be placed directly up against the interior surface, as this could lead to an increase in the relative humidity between the wall and the furniture piece. While picture frames (emulated by the acrylic plates) installed 1.5 cm from the interior surface of the wall, should not result in microclimate with critical relative humidity levels.

5.1.2 Surface treatments

Based on the experimental test, the following indications have been noticed regarding the use of diffusion-open and diffusion-tight paint on the interior surfaces:

- The diffusion-tight paint does have an effect on the vapour permeability of the Multipor insulation system, the diffusion-tight paint could in time have a negative effect on the insulation system.
- However, the effect of each layer of the diffusion-tight paint is quite small. No large differences were noticed between the use of diffusion-open and diffusion-tight paint on the interior surfaces with respect to the relative humidity when using just a few layers of regular paint.

5.2 System specific indications: Multipor

5.2.1 Robustness

Based on the experimental test, the following indications have been noticed regarding the robustness of the Multipor insulation system:

- Based on the performance of the Multipor insulation system in the Hard body impact test, the system is considered acceptable for indoor use against hits from occupants and items.
- The withdrawal and displacement test indicated that the larger and wider plug types performed better when mounted on the Multipor interior insulation system, in comparison to the smaller and thinner plug types.
- The results indicate that the Multipor system performed generally well with respect to the displacement test, however, poorly in the withdrawal test due to the porosity of the material.

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